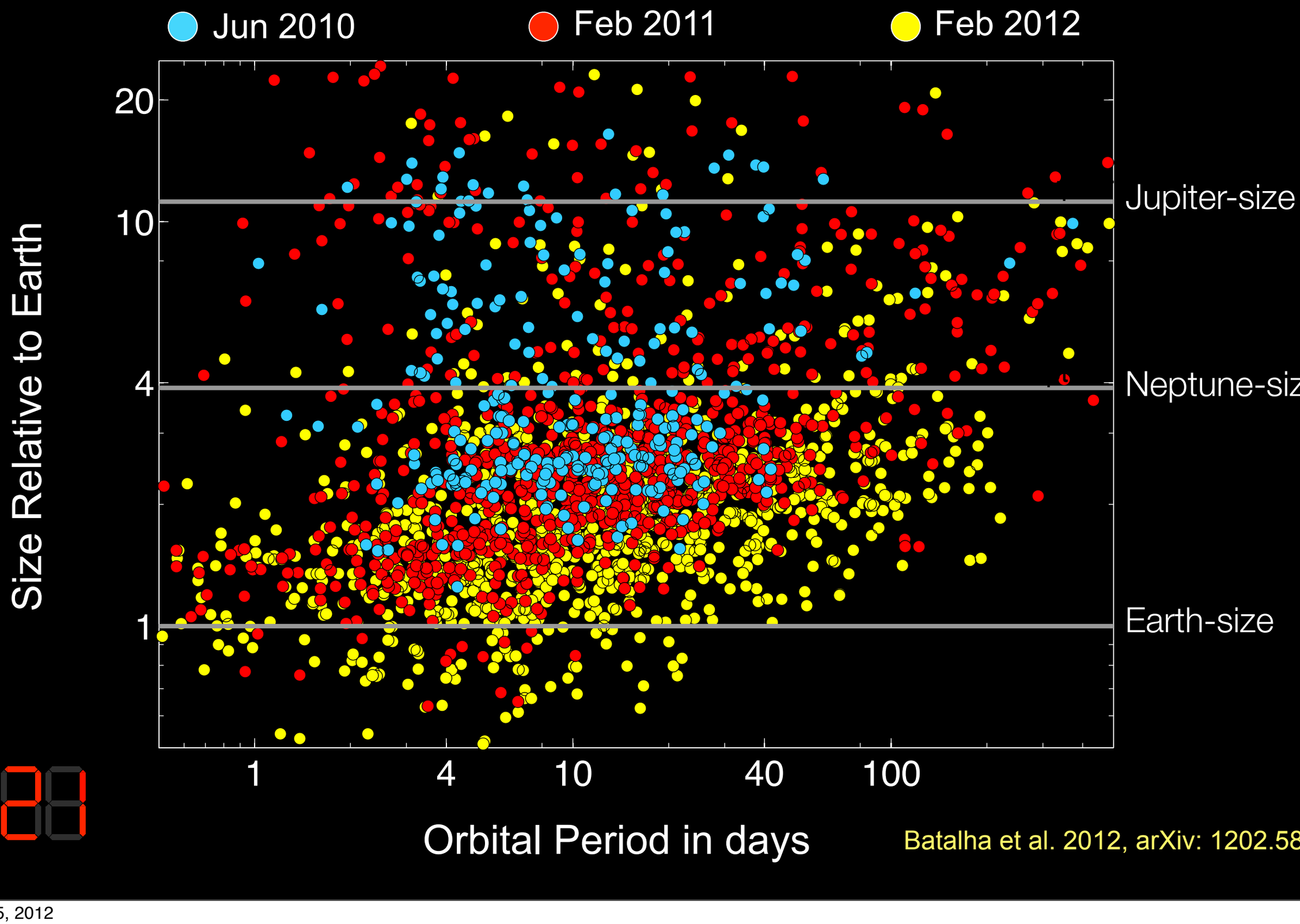
Onward!

Kepler's Exoplanet Census

Natalie Batalha
NASA Ames Research Center

Candidates as of Feb 2012

Q0-Q6: May 2009 - Sep 2010

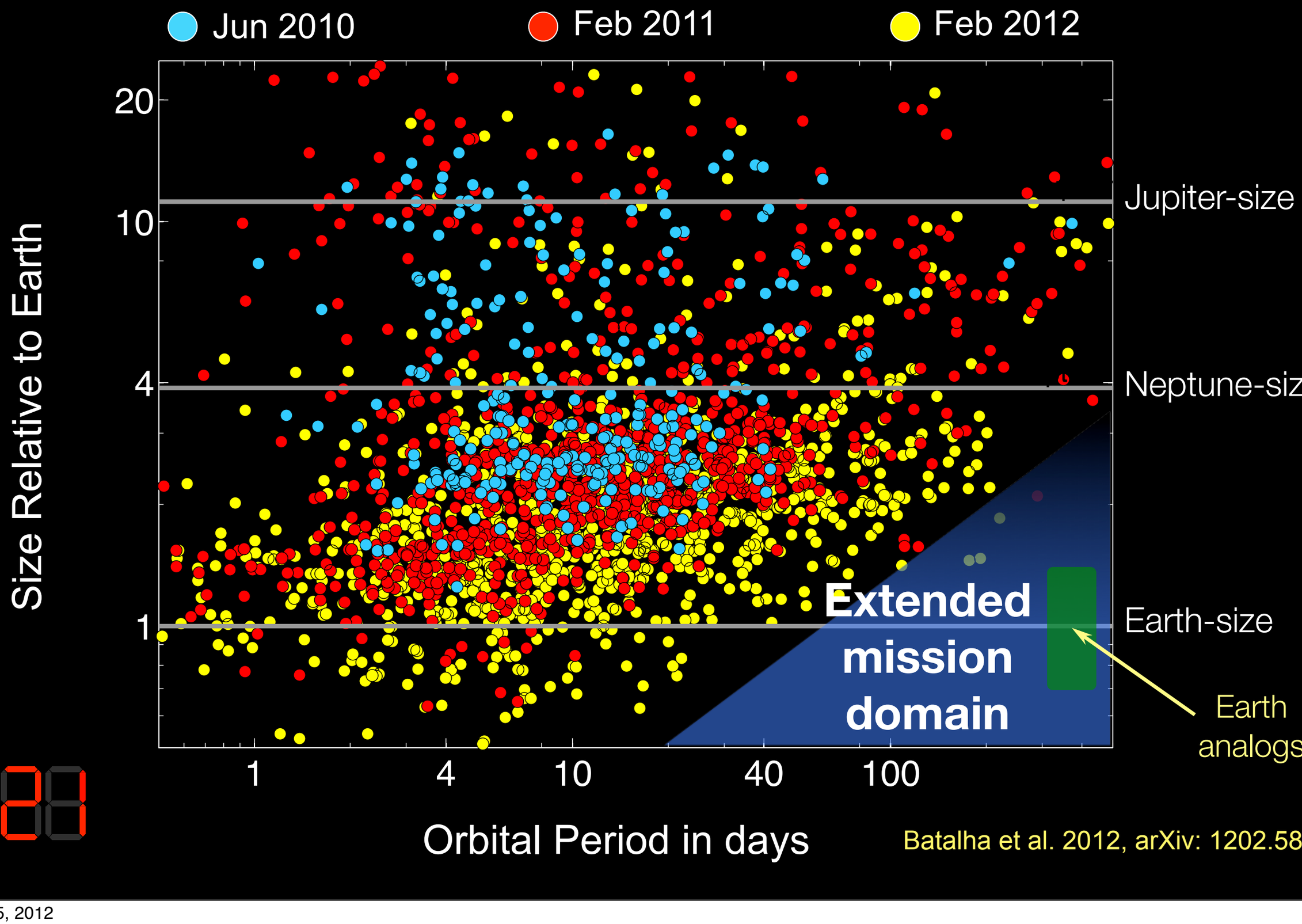


2828

Batalha et al. 2012, arXiv: 1202.5852

Extended Mission

Earth-size planets in the HZ

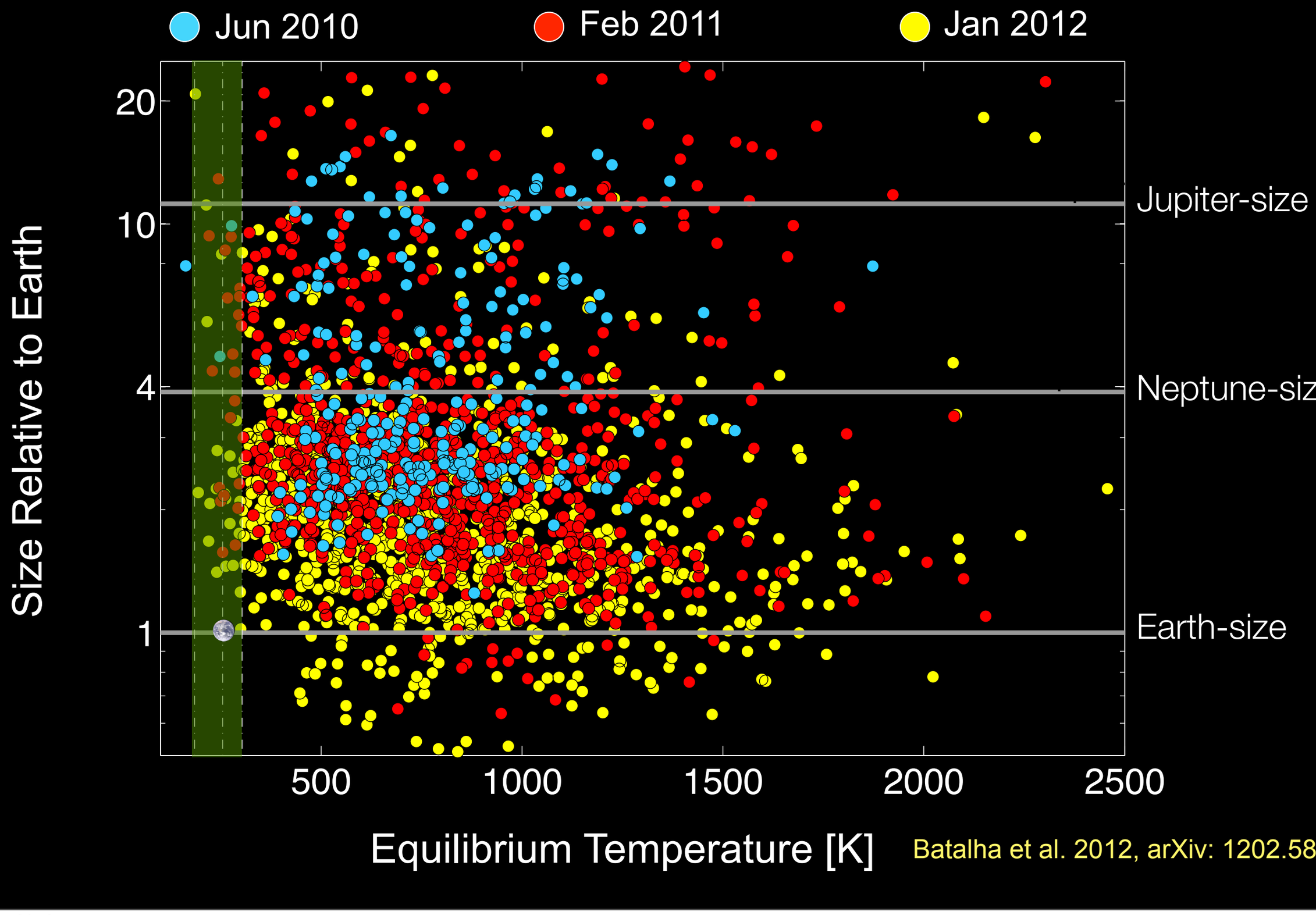


2828

Batalha et al. 2012, arXiv: 1202.5852

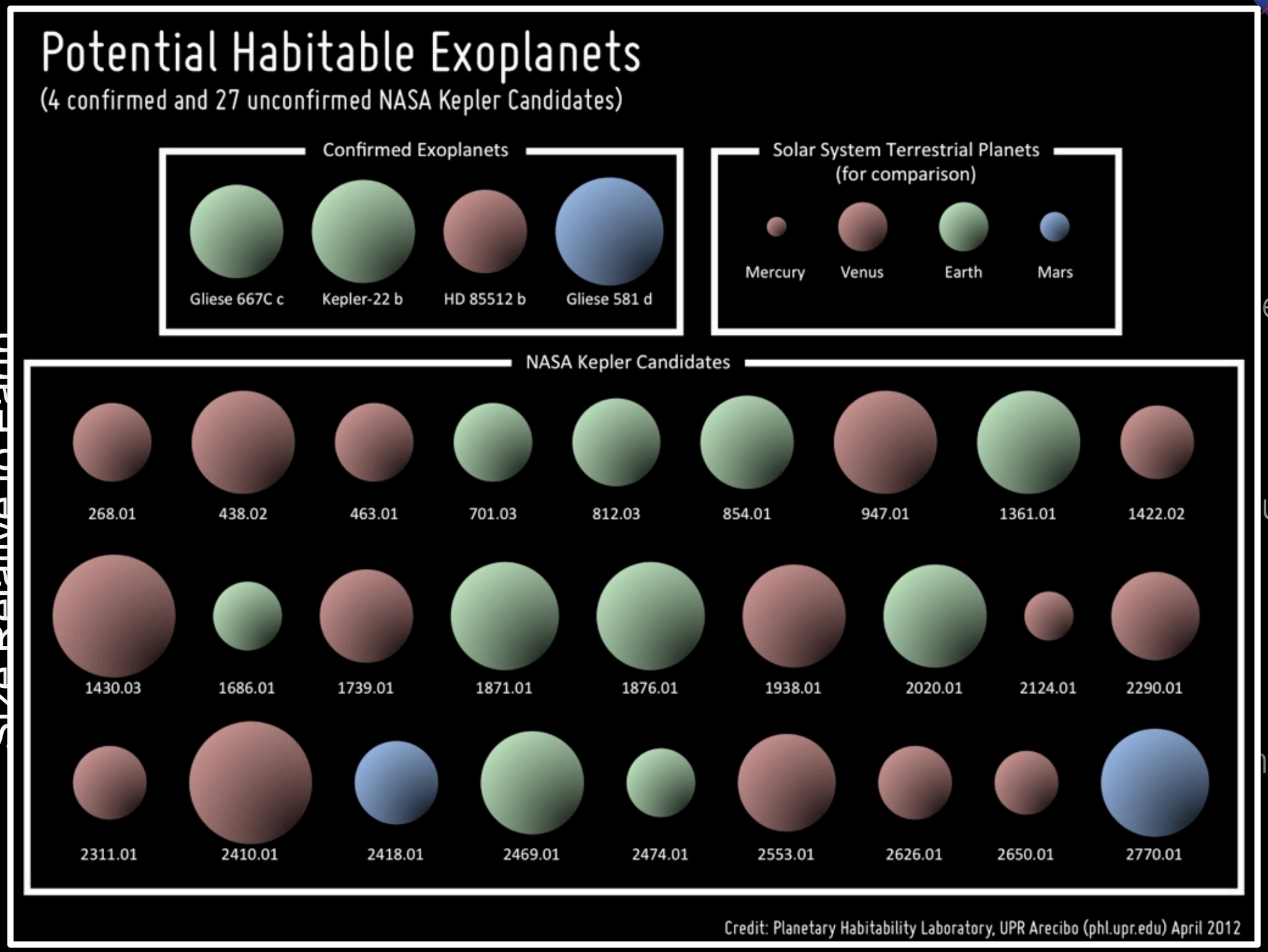
HZ Candidates

48 with T_{eq} between 185 and 303 K



Batalha et al. 2012, arXiv: 1202.5852

HZ Candidates



Size Relative to Earth

er-size

une-size

-size

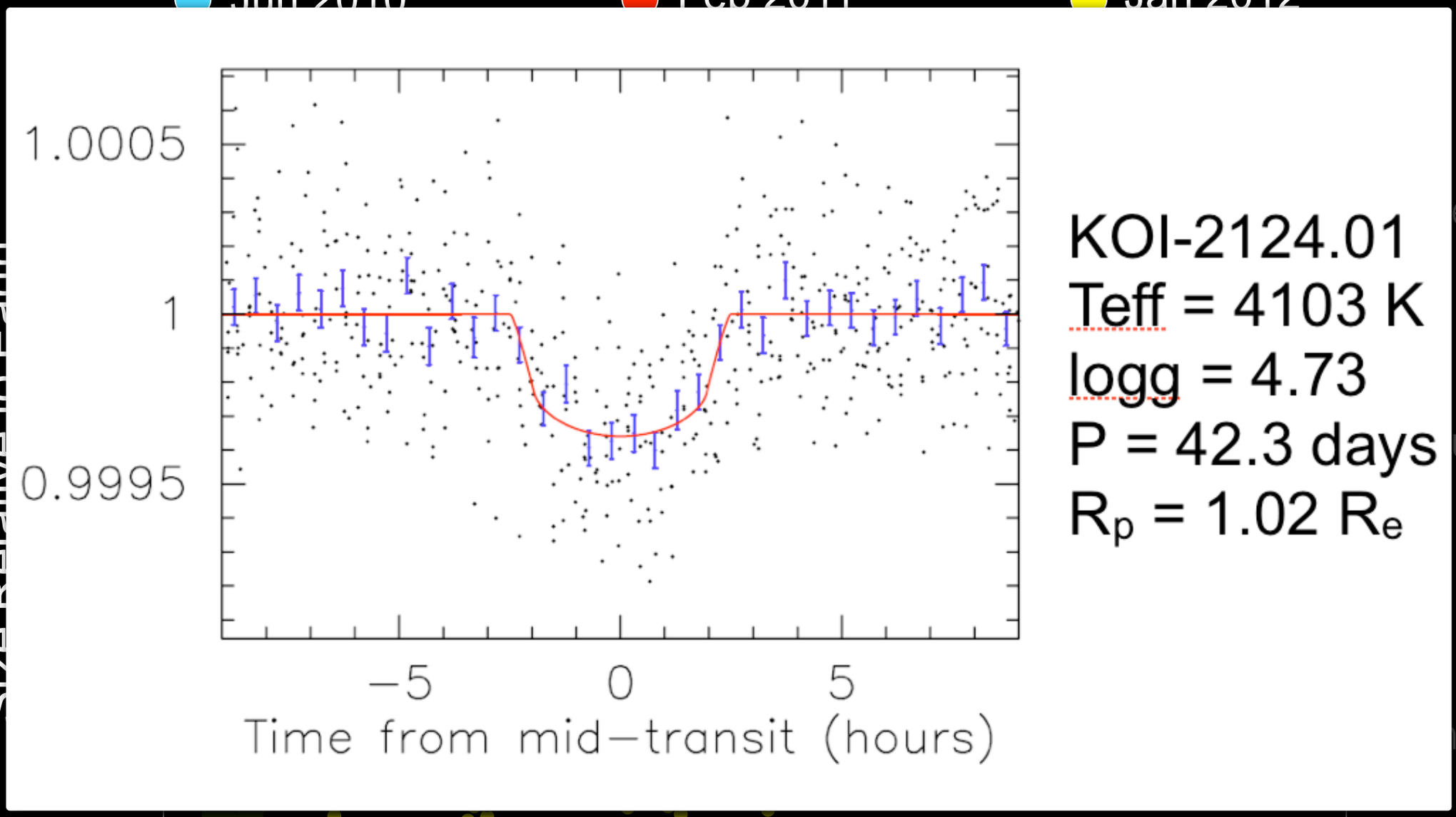
Equilibrium Temperature [K]

Batalha et al. 2012, arXiv: 1202.5852

HZ Candidates

48 with T_{eq} between 185 and 303 K

Jun 2010 Feb 2011 Jan 2012



Size Relative to Earth

er-size

une-size

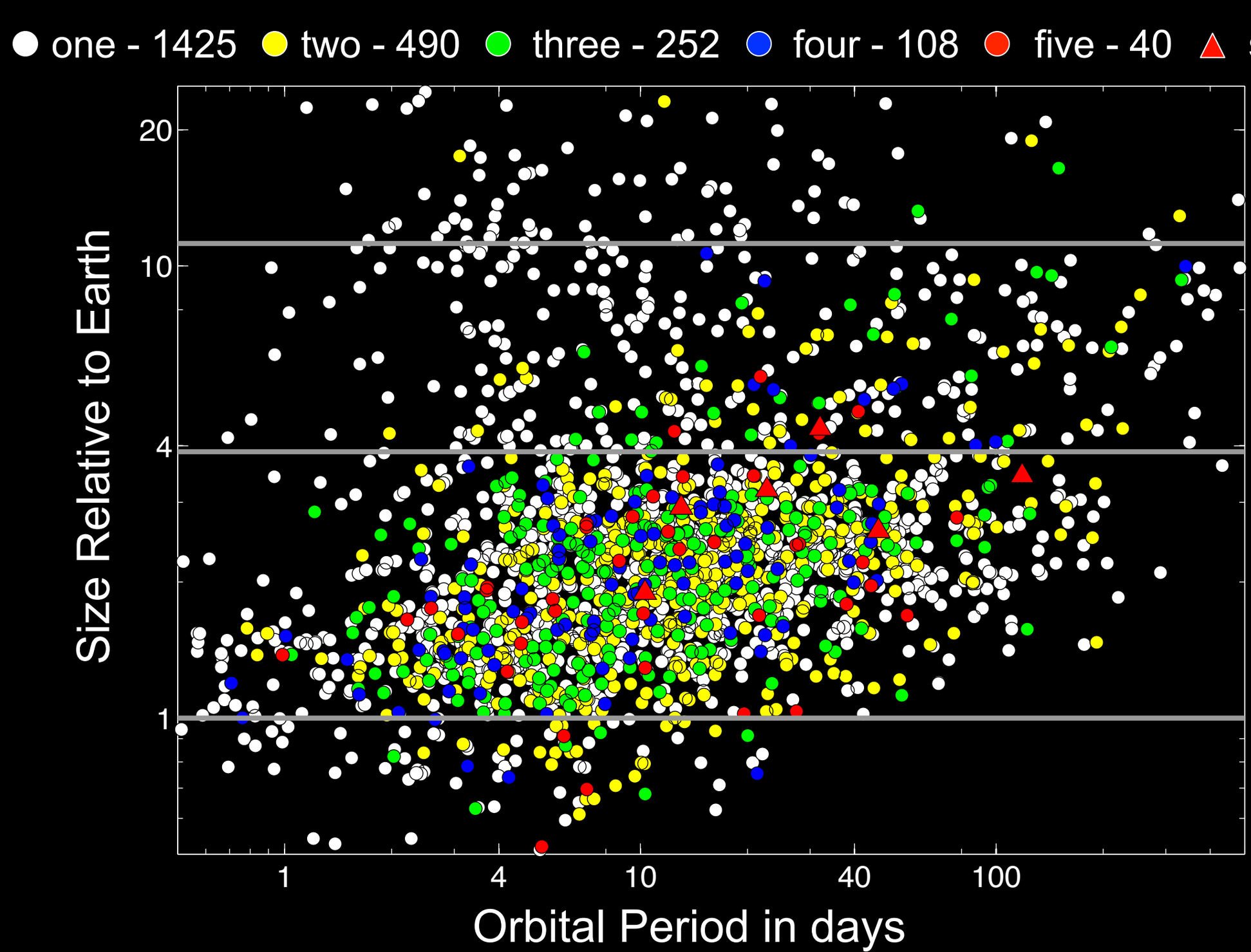
-size

500 1000 1500 2000 2500

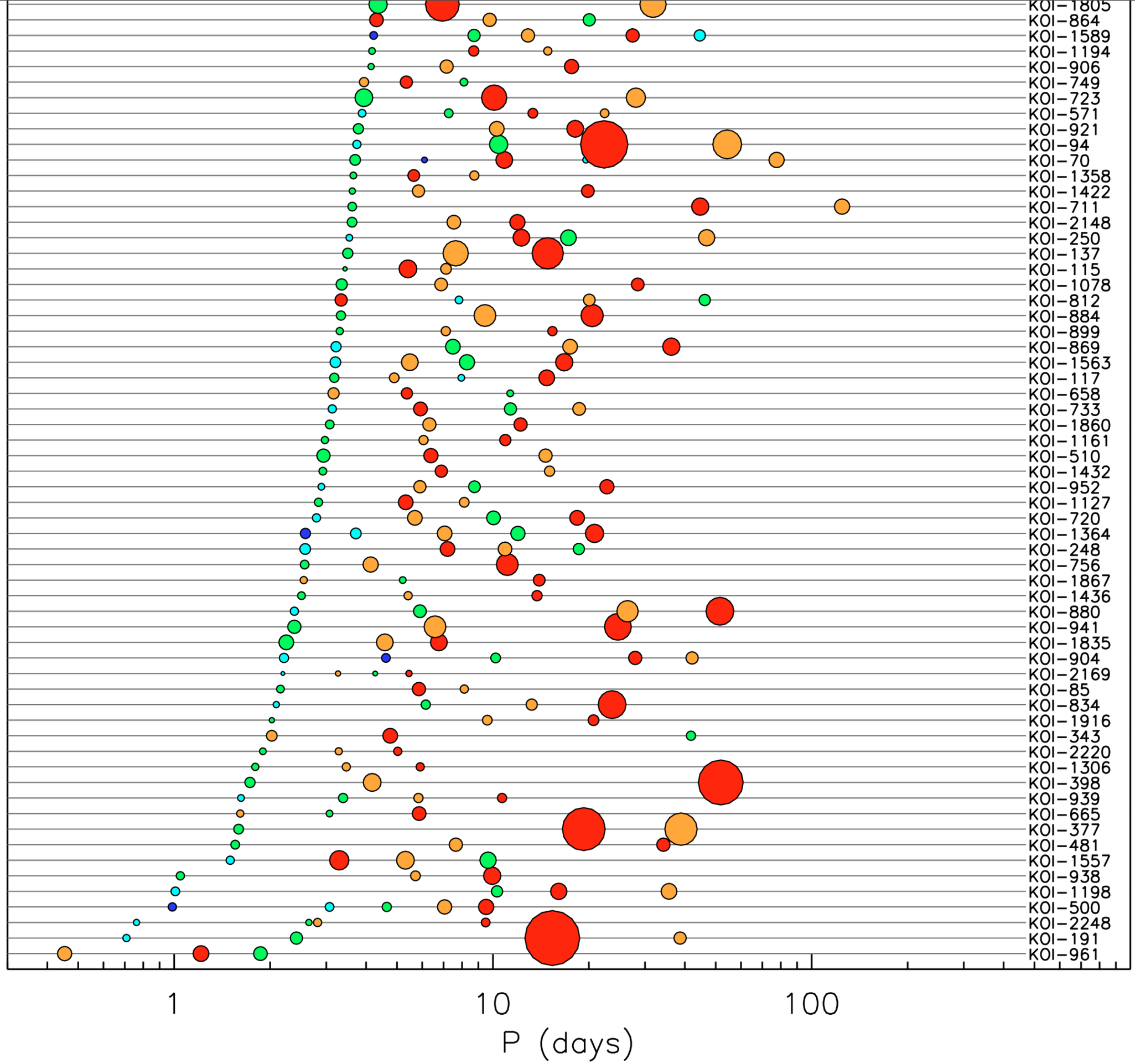
Equilibrium Temperature [K]

Batalha et al. 2012, arXiv: 1202.5852

The Multiples



Batalha et al. 2012, arXiv: 1202.5852


KOI−1805
KOI−864
KOI−1589
KOI−1194
KOI−906
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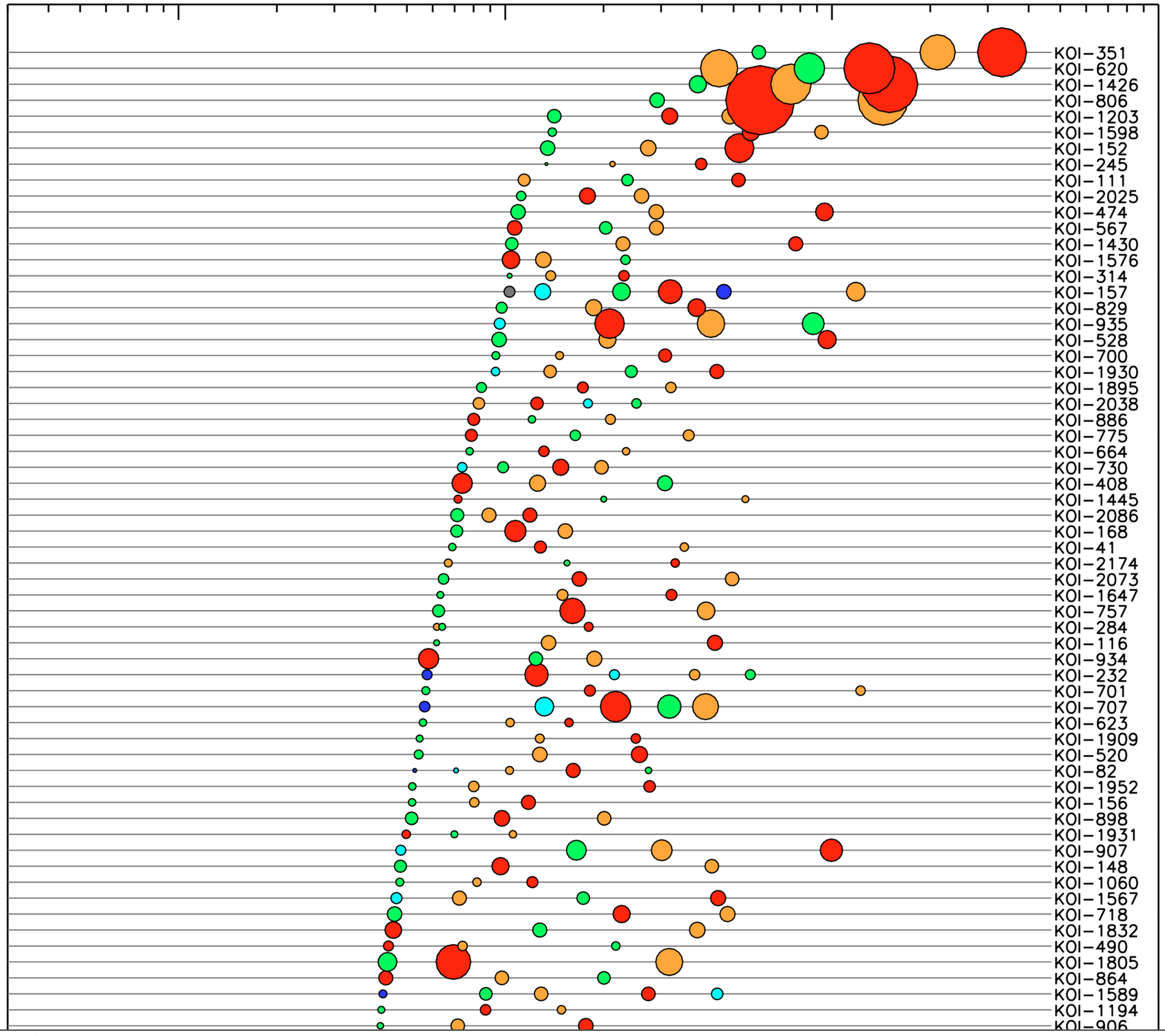
KOI−94
KOI−70
KOI−1358
KOI−1422
KOI−711
KOI−2148
KOI−250
KOI−137
KOI−115
KOI−1078
KOI−812
KOI−884
KOI−899
KOI−869
KOI−1563
KOI−117
KOI−658
KOI−733
KOI−1860
KOI−1161
KOI−510
KOI−1432
KOI−952
KOI−1127
KOI−720
KOI−1364
KOI−248
KOI−756
KOI−1867
KOI−1436
KOI−880
KOI−941
KOI−1835
KOI−904
KOI−2169
KOI−85
KOI−834
KOI−1916
KOI−343
KOI−2220
KOI−1306
KOI−398
KOI−939
KOI−665
KOI−377
KOI−481
KOI−1557
KOI−938
KOI−1198
KOI−500
KOI−2248
KOI−191
KOI−961
1
10
100
P (days)


KOI-351
KOI-620
KOI-1426
KOI-806
KOI-1203
KOI-1598
KOI-152
KOI-245
KOI-111
KOI-2025
KOI-474
KOI-567
KOI-1430
KOI-1576
KOI-314
KOI-157
KOI-829
KOI-935
KOI-528
KOI-700
KOI-1930
KOI-1895
KOI-2038
KOI-886
KOI-775
KOI-664
KOI-730
KOI-408
KOI-1445
KOI-2086
KOI-168
KOI-41
KOI-2174
KOI-2073
KOI-1647
KOI-757
KOI-284
KOI-116
KOI-934
KOI-232
KOI-701
KOI-707
KOI-623
KOI-1909
KOI-520
KOI-82
KOI-1952
KOI-156
KOI-898
KOI-1931
KOI-907
KOI-148
KOI-1060
KOI-1567
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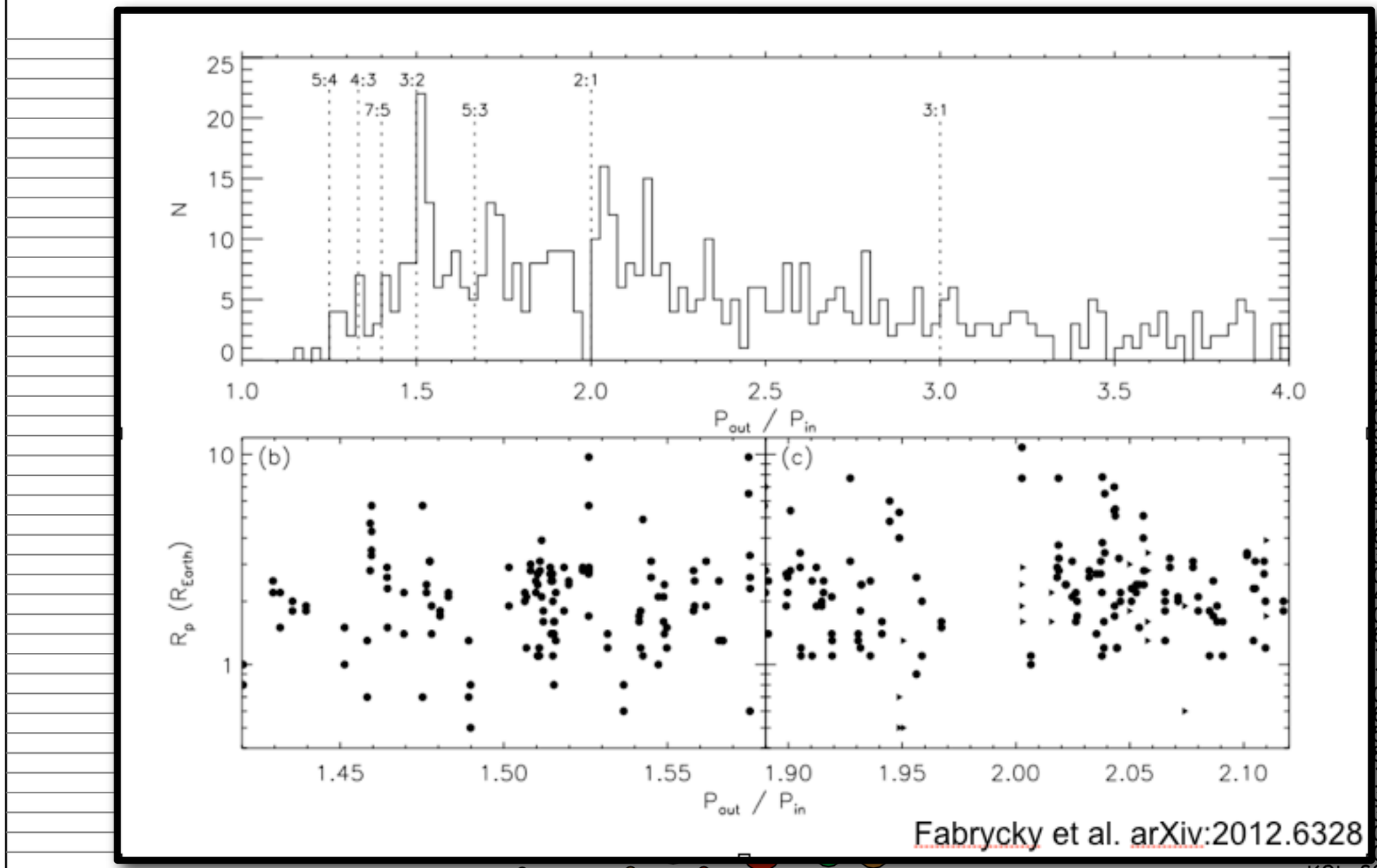
KOI-1832
KOI-490
KOI-1805
KOI-864
KOI-1589
KOI-1194
KOI-906


5:4
4:3
7:5
3:2
5:3
2:1
3:1
N
P_out / P_in
(b)
(c)
R_p (R_Earth)
Fabrycky et al. arXiv:2012.6328

KOI-623
KOI-1909
KOI-520
KOI-82
KOI-1952
KOI-156
KOI-898
KOI-1931
KOI-907
KOI-148
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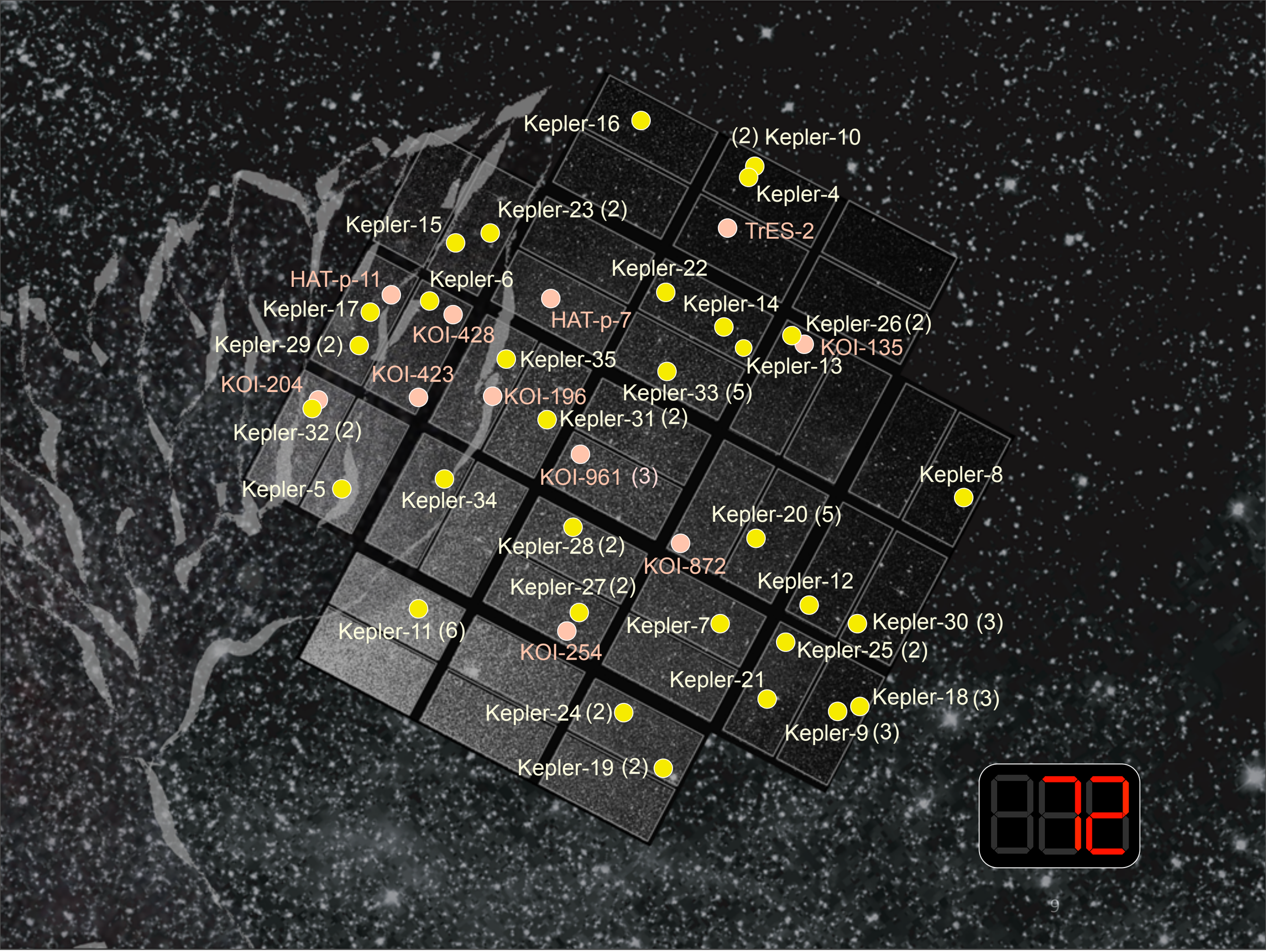
KOI-864
KOI-1589
KOI-1194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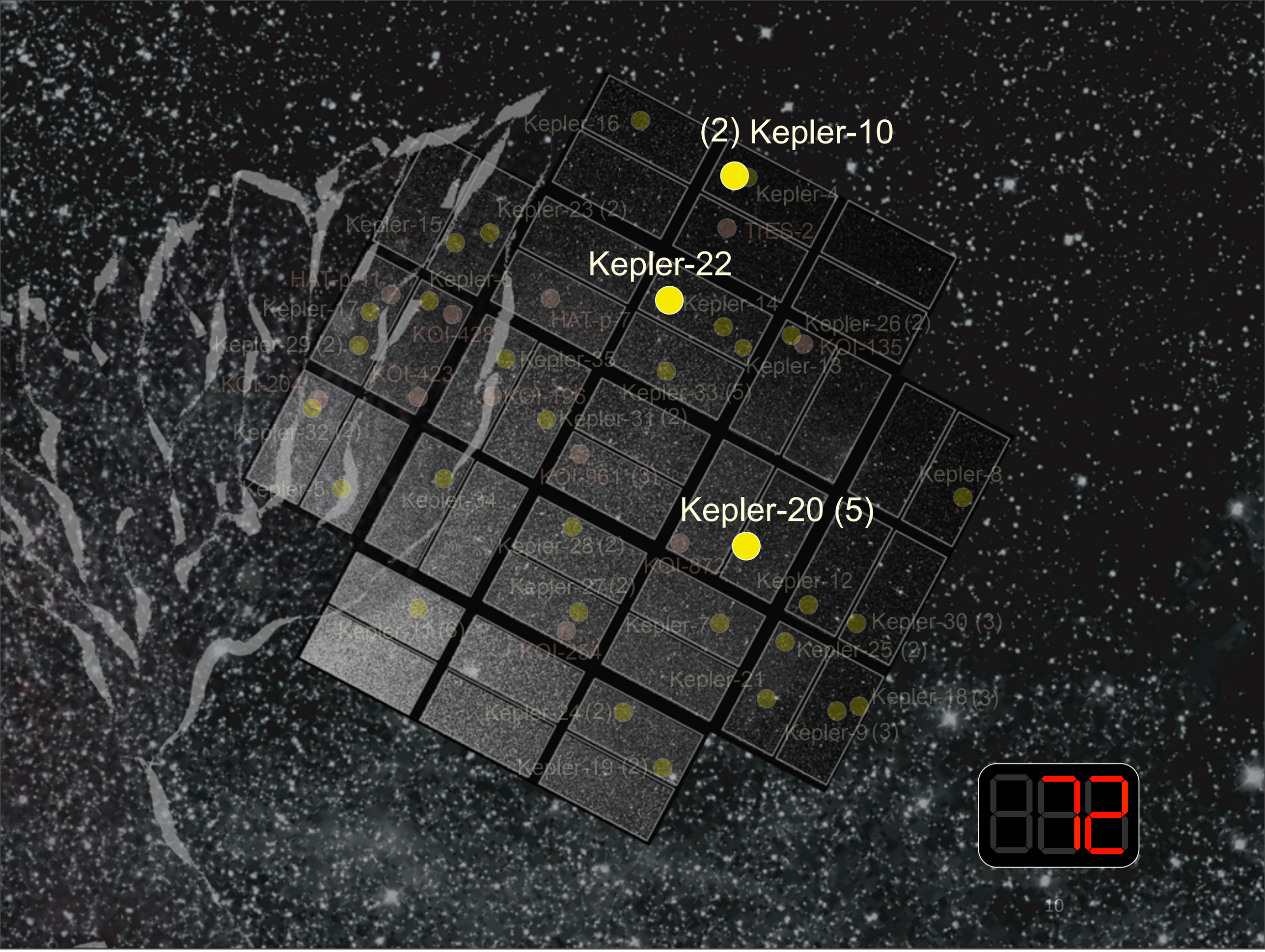
(2) Kepler-10
Kepler-4
Kepler-23 (2)
Kepler-15
TrES-2
Kepler-22
HAT-p-11
Kepler-6
Kepler-17
HAT-p-7
Kepler-14
Kepler-26 (2)
KOI-428
KOI-135
Kepler-29 (2)
Kepler-35
Kepler-13
KOI-423
KOI-204
KOI-196
Kepler-33 (5)
Kepler-31 (2)
Kepler-32 (2)
KOI-961 (3)
Kepler-8
Kepler-5
Kepler-34
Kepler-20 (5)
Kepler-28 (2)
KOI-872
Kepler-12
Kepler-27 (2)
Kepler-30 (3)
Kepler-11 (6)
Kepler-7
Kepler-25 (2)
KOI-254
Kepler-21
Kepler-18 (3)
Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)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(2) Kepler-10
Kepler-4
Kepler-23 (2)
Kepler-15
TrES-2
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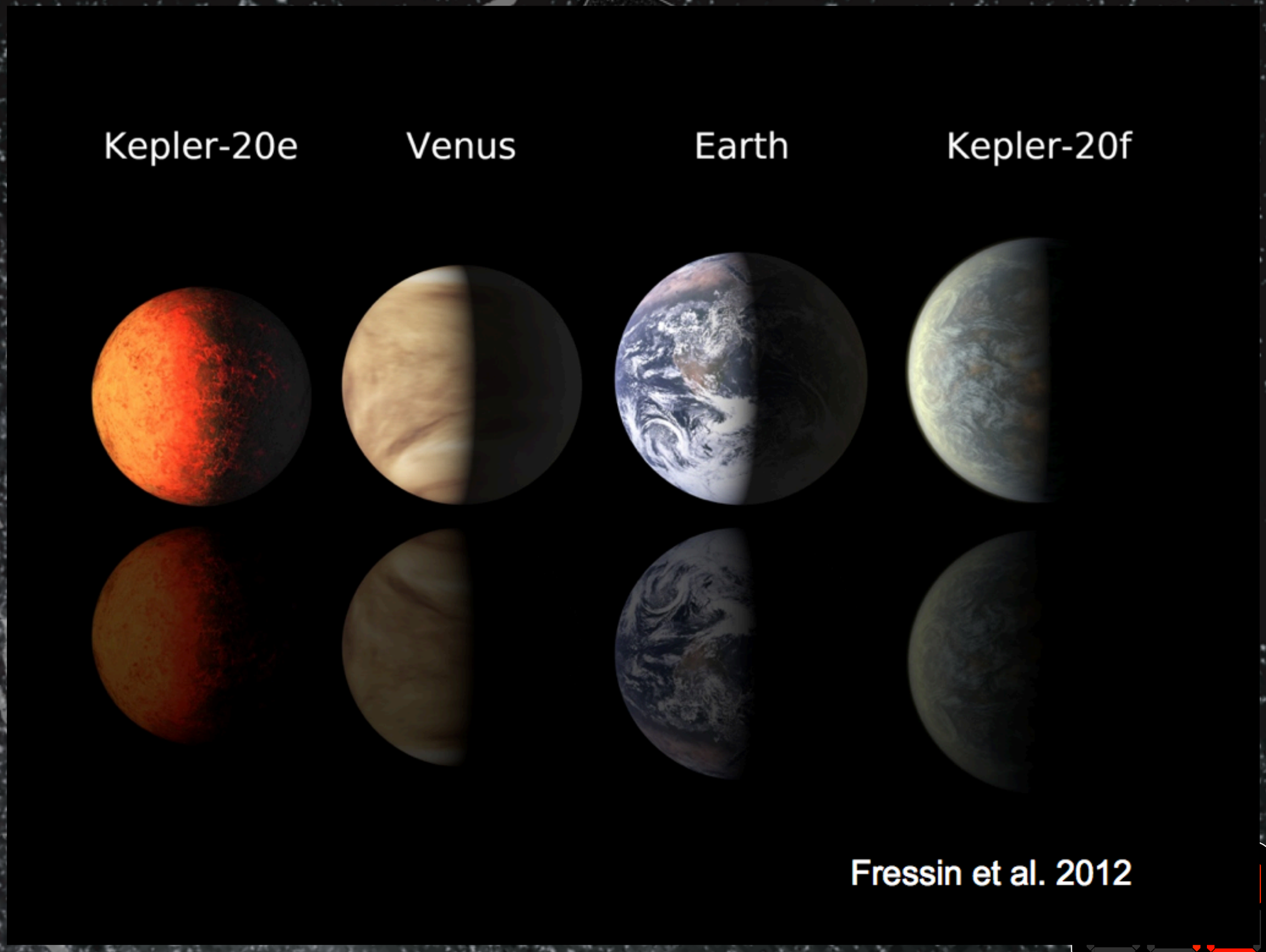
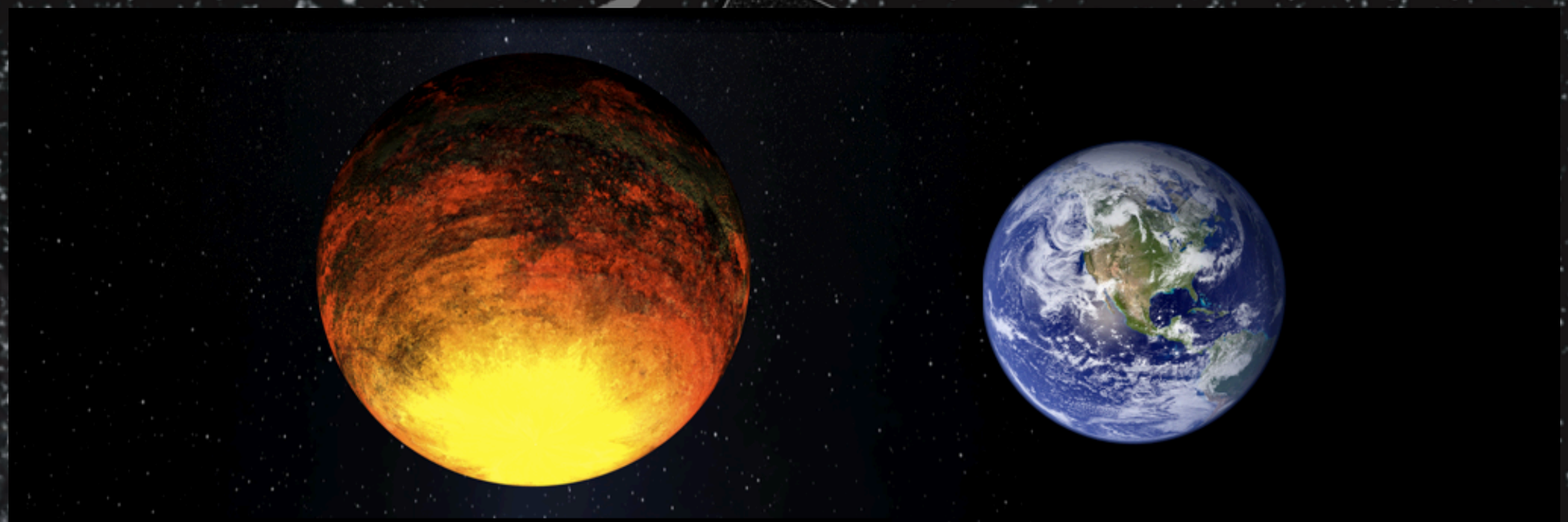
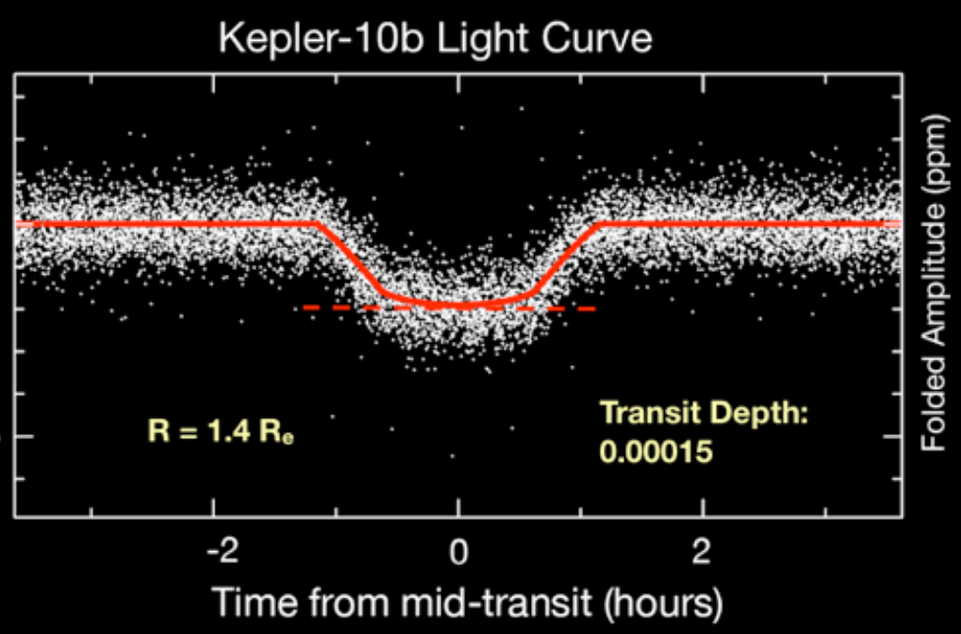
KOI-254
Kepler-21
Kepler-18 (3)
Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)

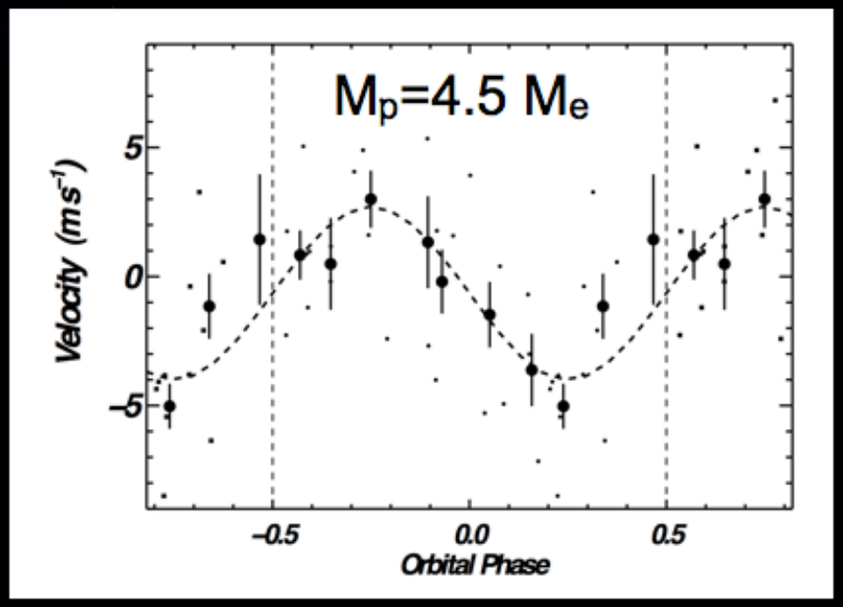

Kepler-20e
Venus
Earth
Kepler-20f
Fressin et al. 2012

Kepler-22b
P=289.8623 days
R_p=2.38±0.13 $R_\oplus$
T_{eq}=262 K
Borucki et al. 2012, ApJ, 745, 120

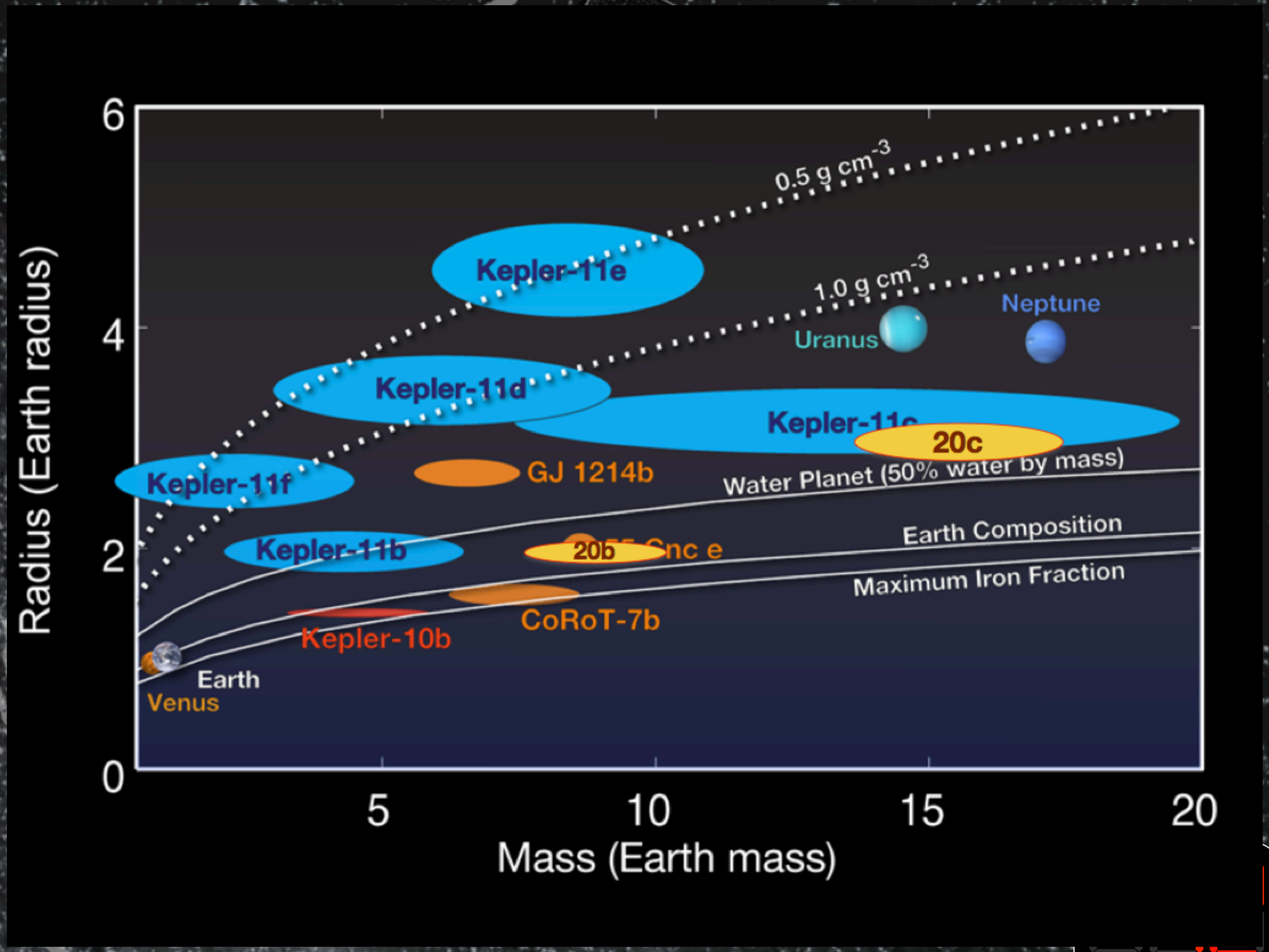


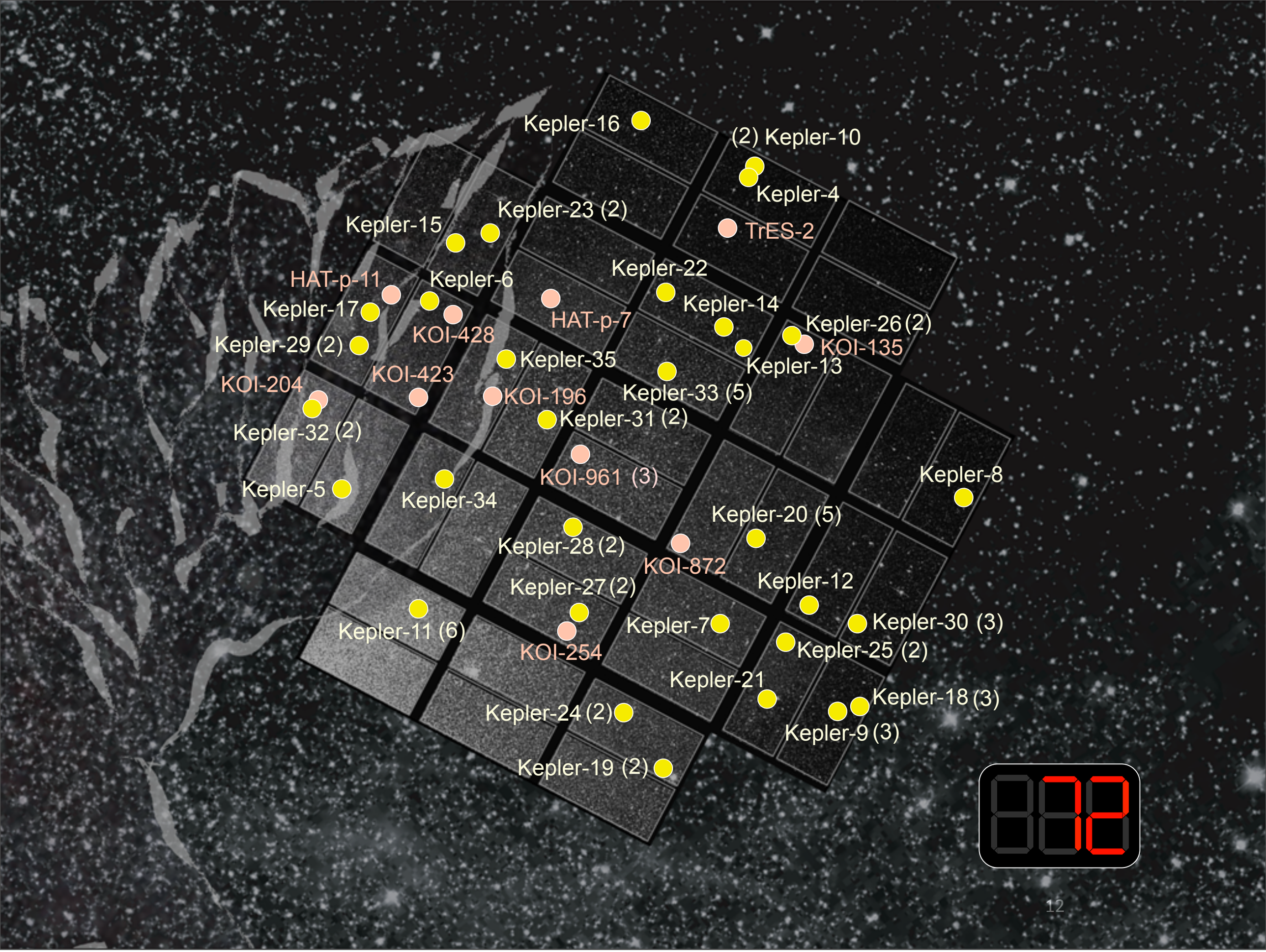


Total SNR > 140 (22 months of data)



Batalha et al. 2011, ApJ, 729, 27


6
4
2
0
Radius (Earth radius)
5
10
15
20
Mass (Earth mass)
0.5 g cm-3
1.0 g cm-3
Kepler-11e
Kepler-11d
Kepler-11c
Kepler-11f
GJ 1214b
20c
Water Planet (50% water by mass)
Kepler-11b
20b
nc e
Earth Composition
Maximum Iron Fraction
CoRoT-7b
Kepler-10b
Earth
Venus
Uranus
Neptune


Kepler-16
(2) Kepler-10
Kepler-4
Kepler-23 (2)
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HAT-p-11
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KOI-254
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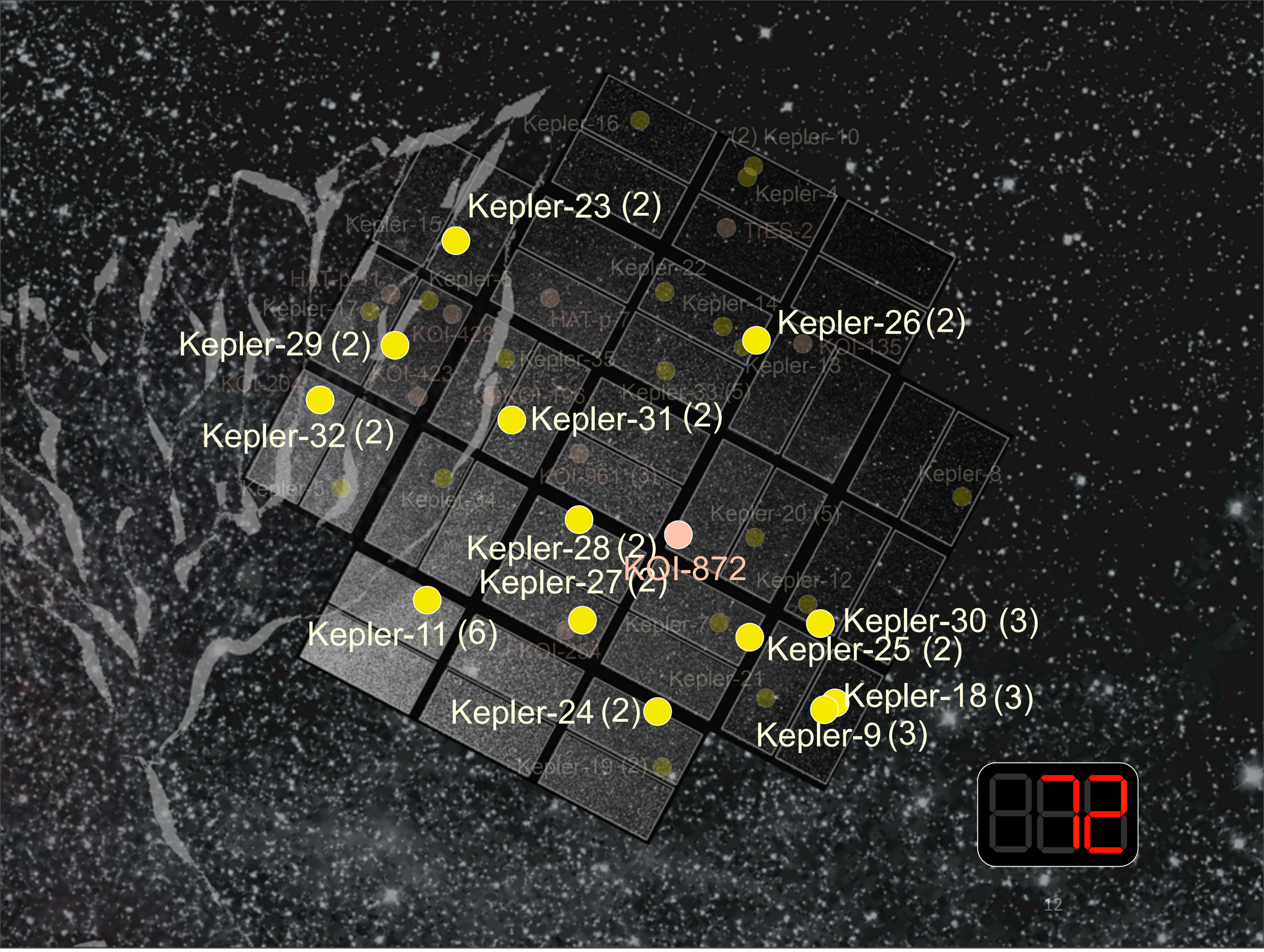
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KOI-254
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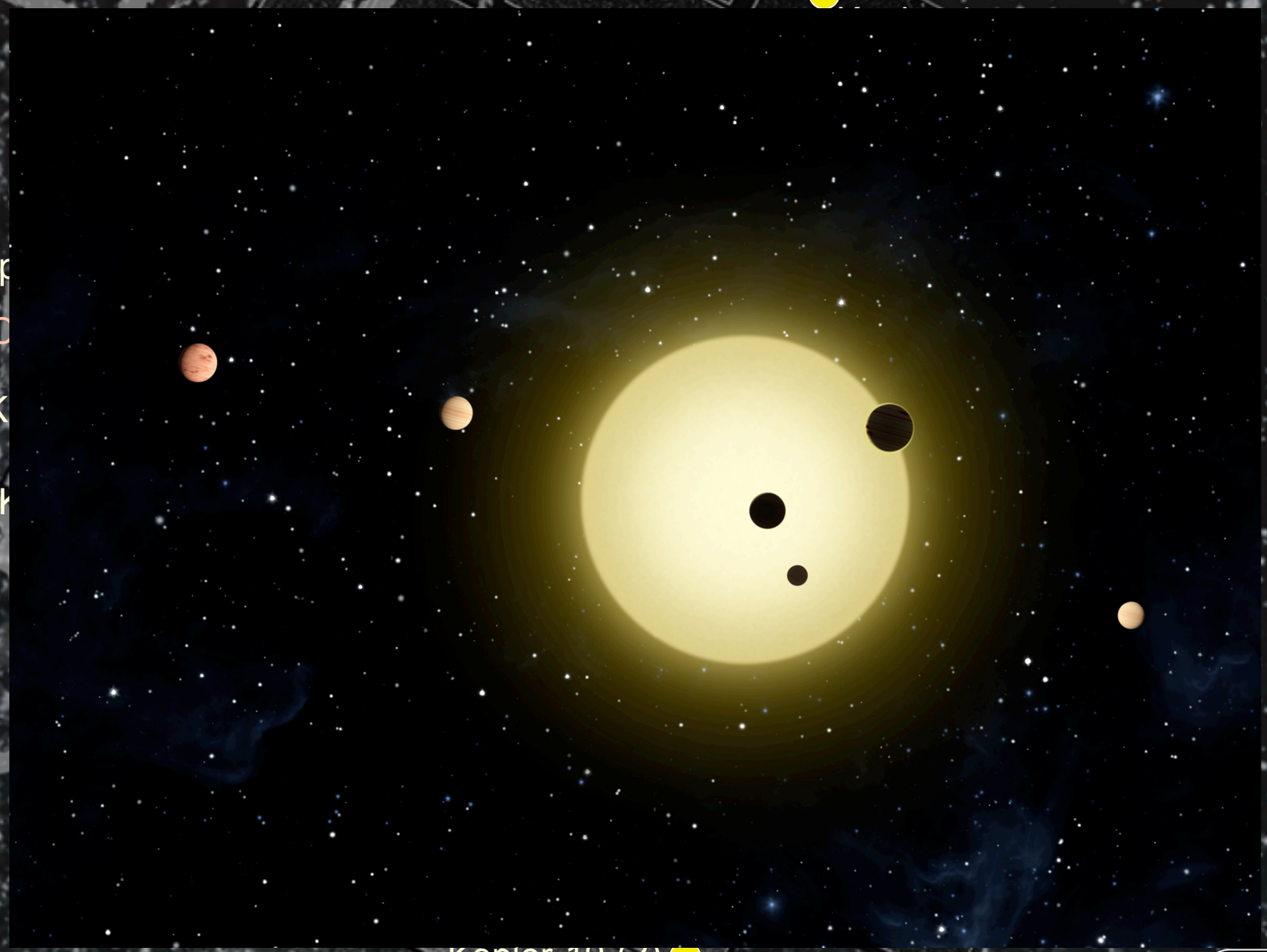
Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)
12

Kepler-16

(2) Kepler-10



Kep

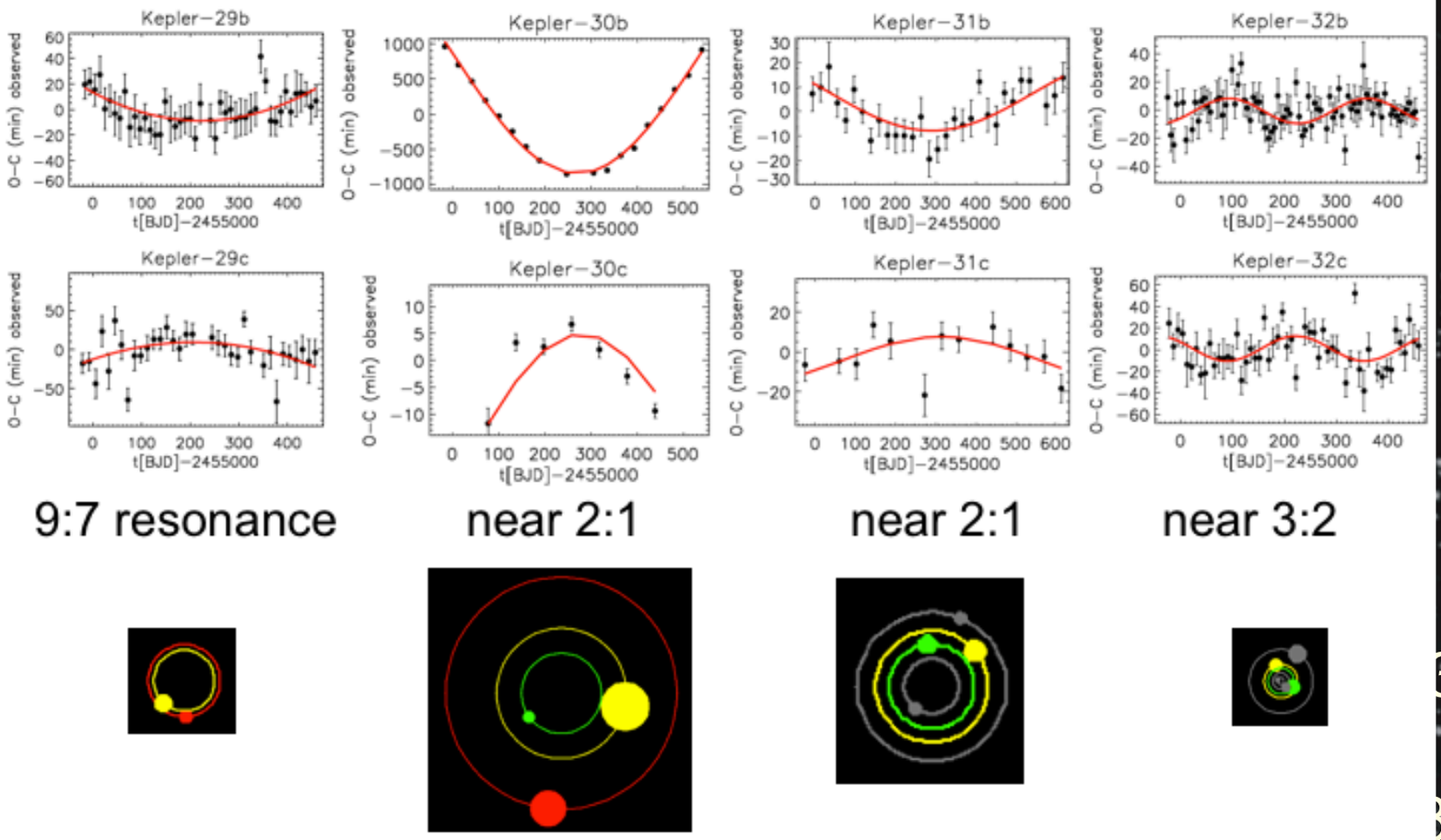
KO

K

K

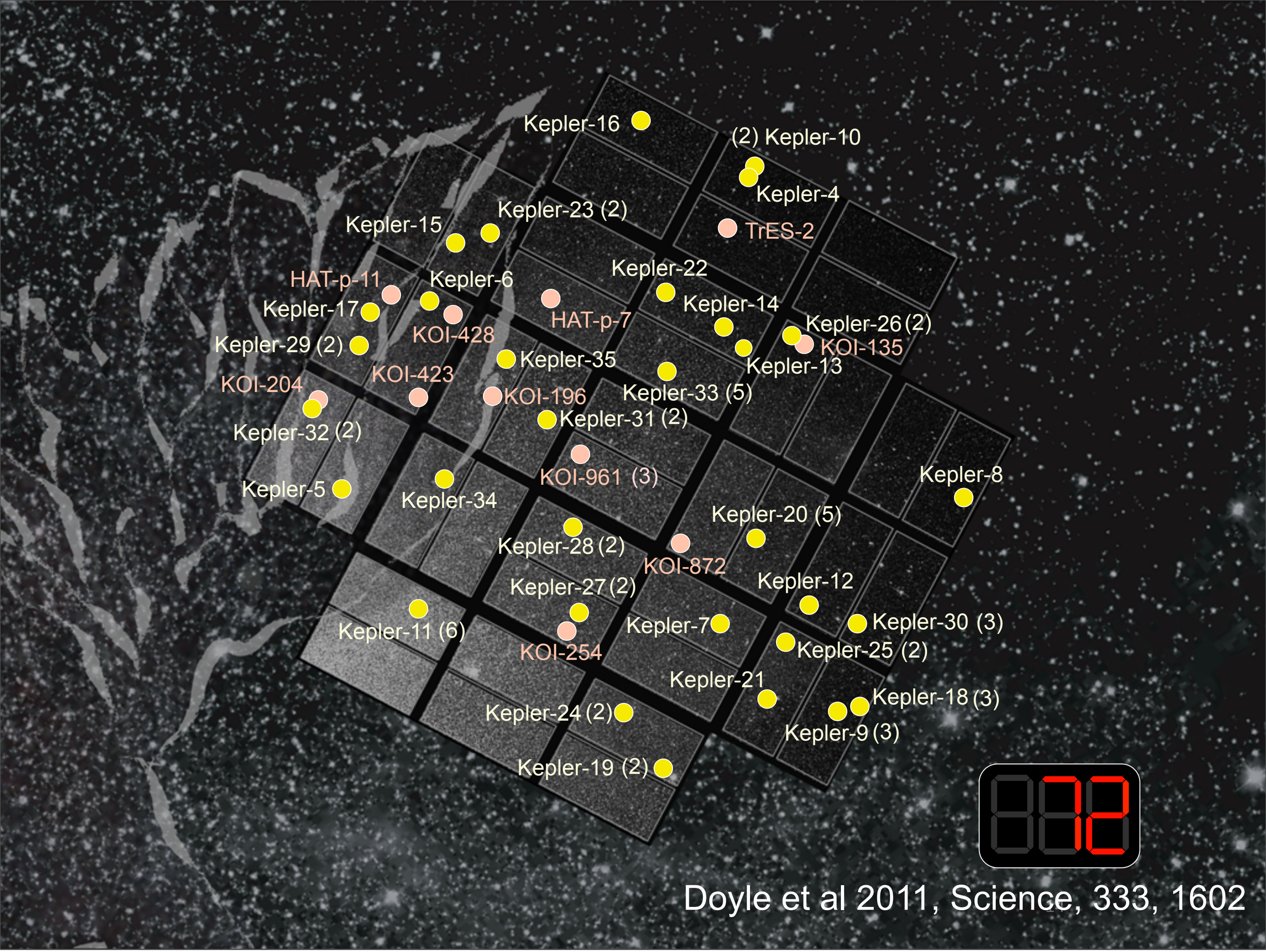
Kepler-19 (2)

Other Systems: A TTV-Confirmation Catalog



9:7 resonance | near 2:1 | near 2:1 | near 3:2

Ford et al. 2012, Steffen et al. 2012, Fabrycky et al. 2012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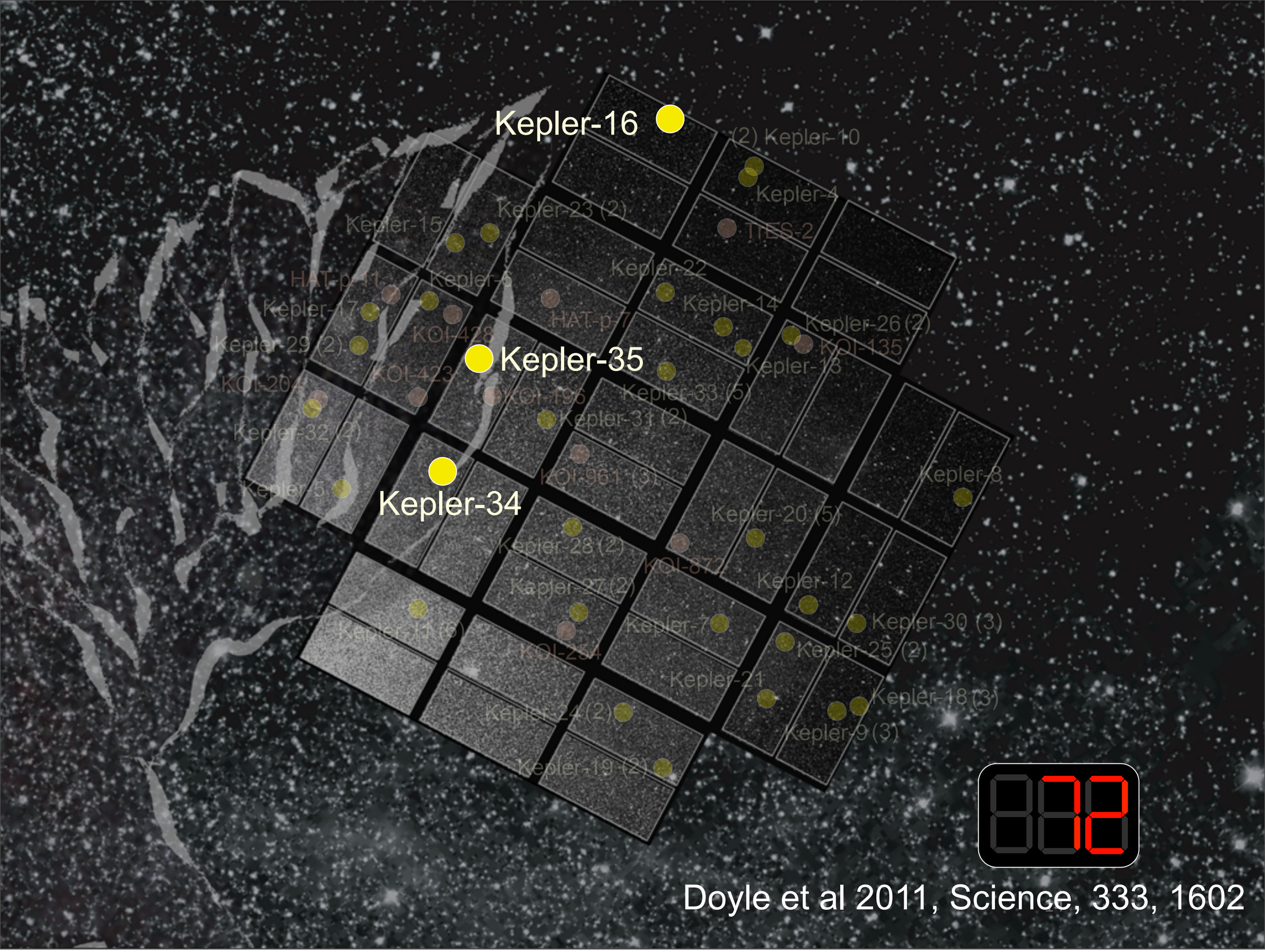
Kepler-19 (2)
Doyle et al 2011, Science, 333, 1602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Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)
Doyle et al 2011, Science, 333, 1602

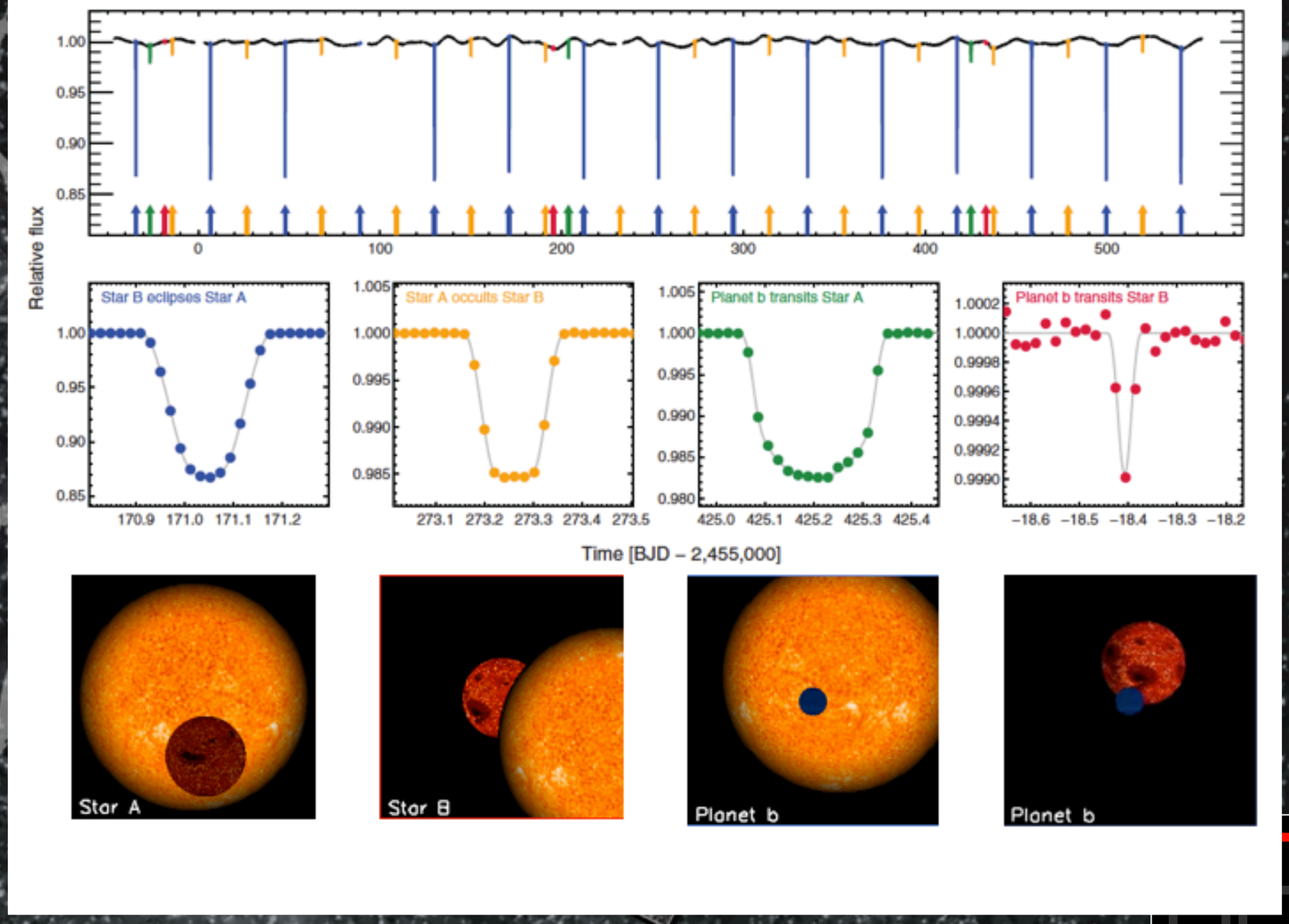
Kepler-16

(2) Kepler-10

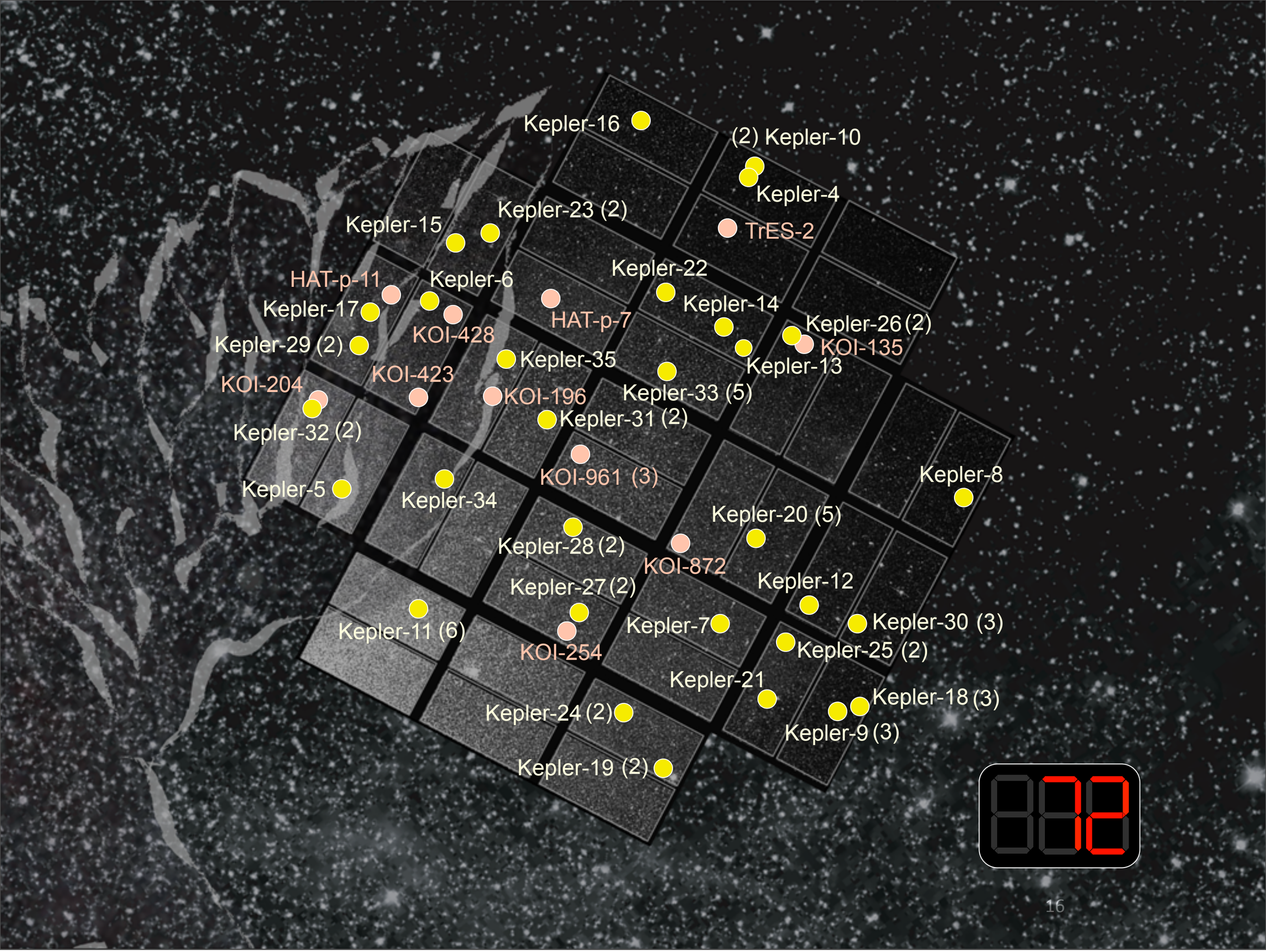
Doyle et al 2011, Science, 333, 1602

Kepler-16

(2) Kepler-10



Doyle et al 2011, Science, 333, 1602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HAT-p-7
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HAT-p-11
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Kepler-17
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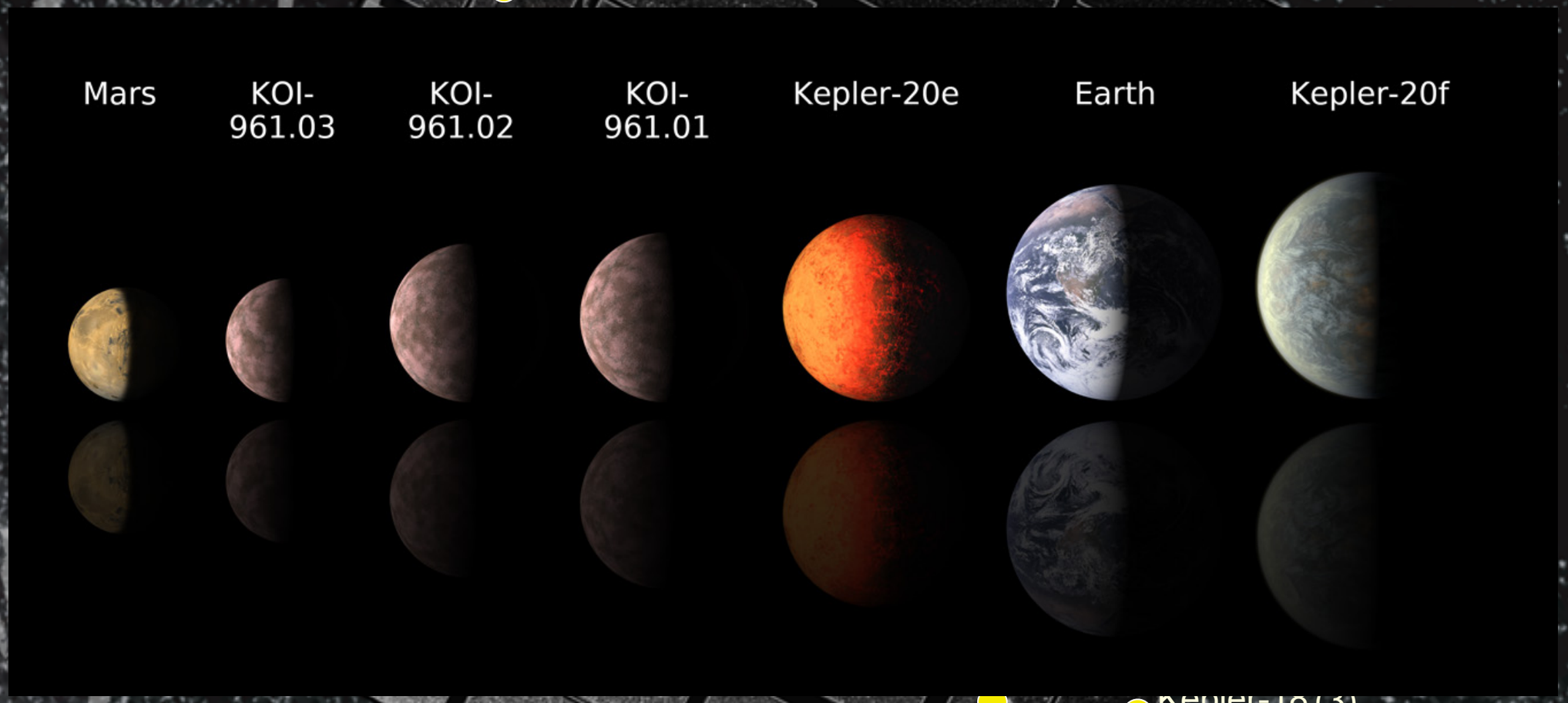
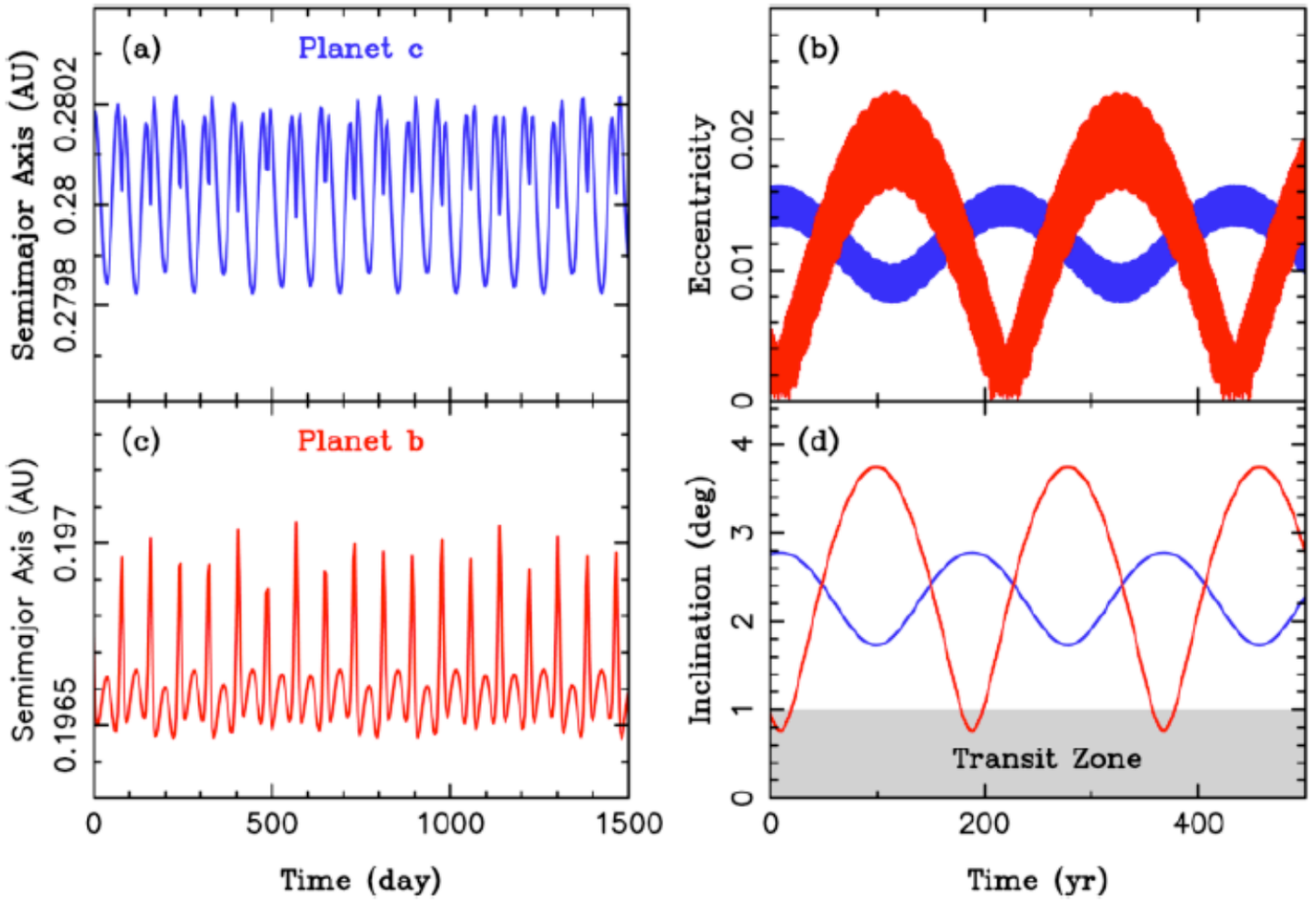
Kepler-19 (2)

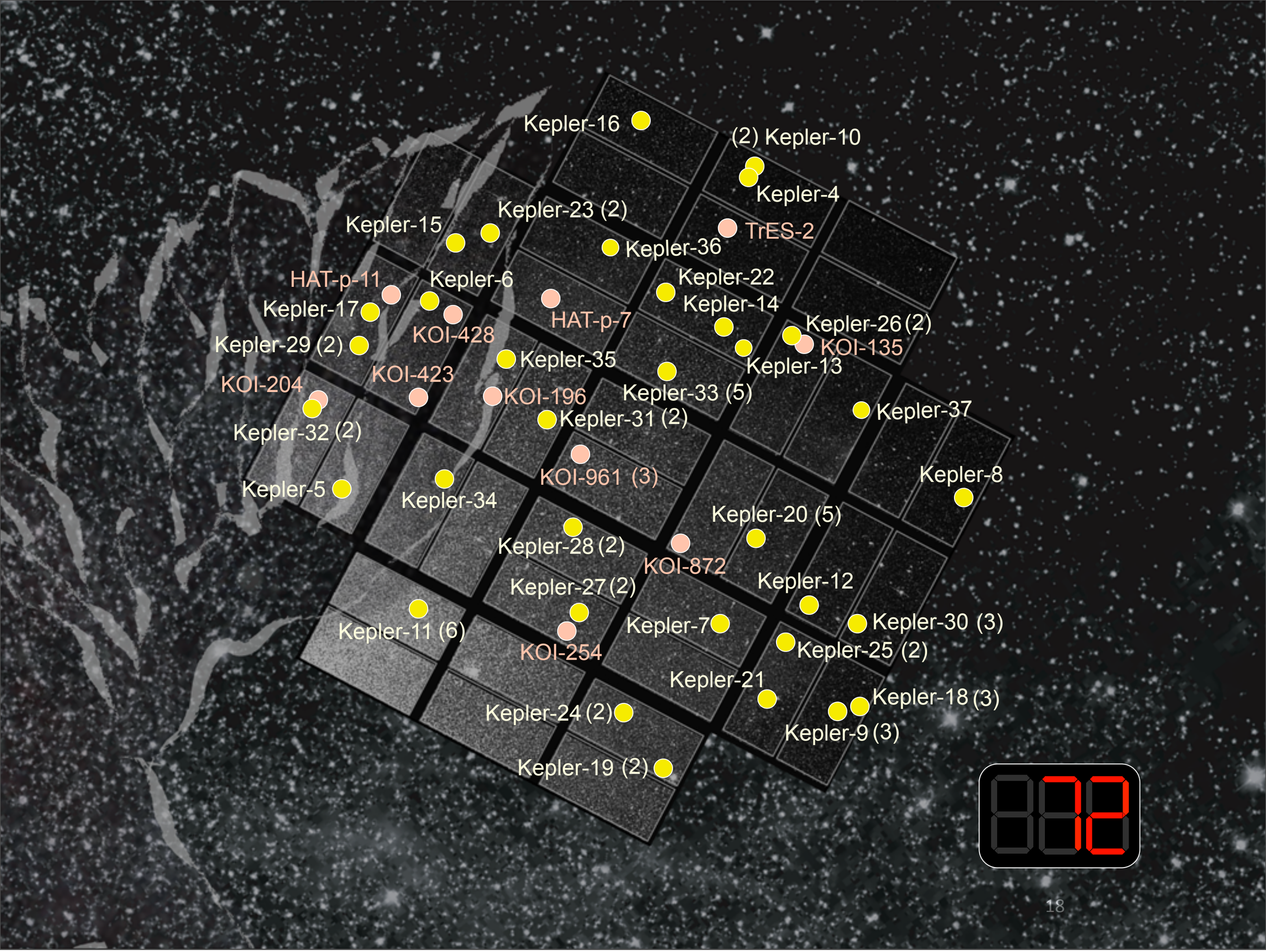


Kepler-16
(2) Kepler-10
Kepler-4
Kepler-23 (2)
Kepler-15
TrES-2
Kepler-24 (2)
Kepler-19 (2)
Kepler-9 (3)

KOI-872 b & c



Nesvorny et al., SciencExpress, 12 May 10


Kepler-16
(2) Kepler-10
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Kepler-15
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HAT-p-11
Kepler-6
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Kepler-17
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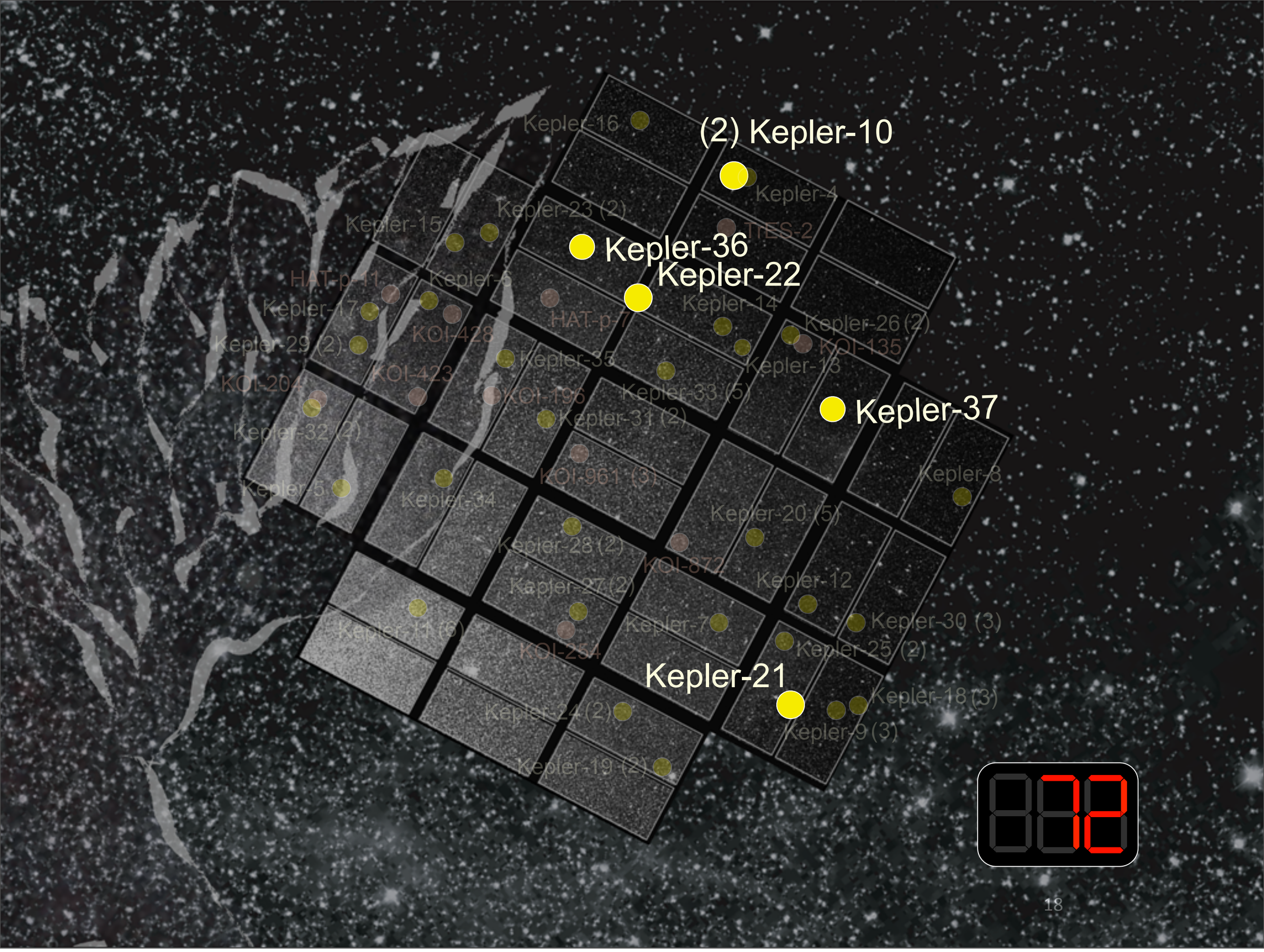
KOI-135
Kepler-29 (2)
Kepler-35
Kepler-13
KOI-423
KOI-204
Kepler-33 (5)
KOI-196
Kepler-37
Kepler-31 (2)
Kepler-32 (2)
KOI-961 (3)
Kepler-8
Kepler-5
Kepler-34
Kepler-20 (5)
Kepler-28 (2)
KOI-872
Kepler-12
Kepler-27 (2)
Kepler-30 (3)
Kepler-11 (6)
Kepler-7
Kepler-25 (2)
KOI-254
Kepler-21
Kepler-18 (3)
Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)


Kepler-16
(2) Kepler-10
Kepler-4
Kepler-23 (2)
Kepler-15
TrES-2
Kepler-36
Kepler-22
HAT-p-11
Kepler-6
Kepler-17
Kepler-14
HAT-p-7
Kepler-26 (2)
KOI-428
KOI-135
Kepler-29 (2)
Kepler-35
Kepler-13
KOI-423
KOI-204
KOI-196
Kepler-33 (5)
Kepler-37
Kepler-31 (2)
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Kepler-8
Kepler-5
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Kepler-20 (5)
Kepler-28 (2)
KOI-872
Kepler-27 (2)
Kepler-12
Kepler-30 (3)
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KOI-254
Kepler-25 (2)
Kepler-21
Kepler-18 (3)
Kepler-24 (2)
Kepler-9 (3)
Kepler-19 (2)

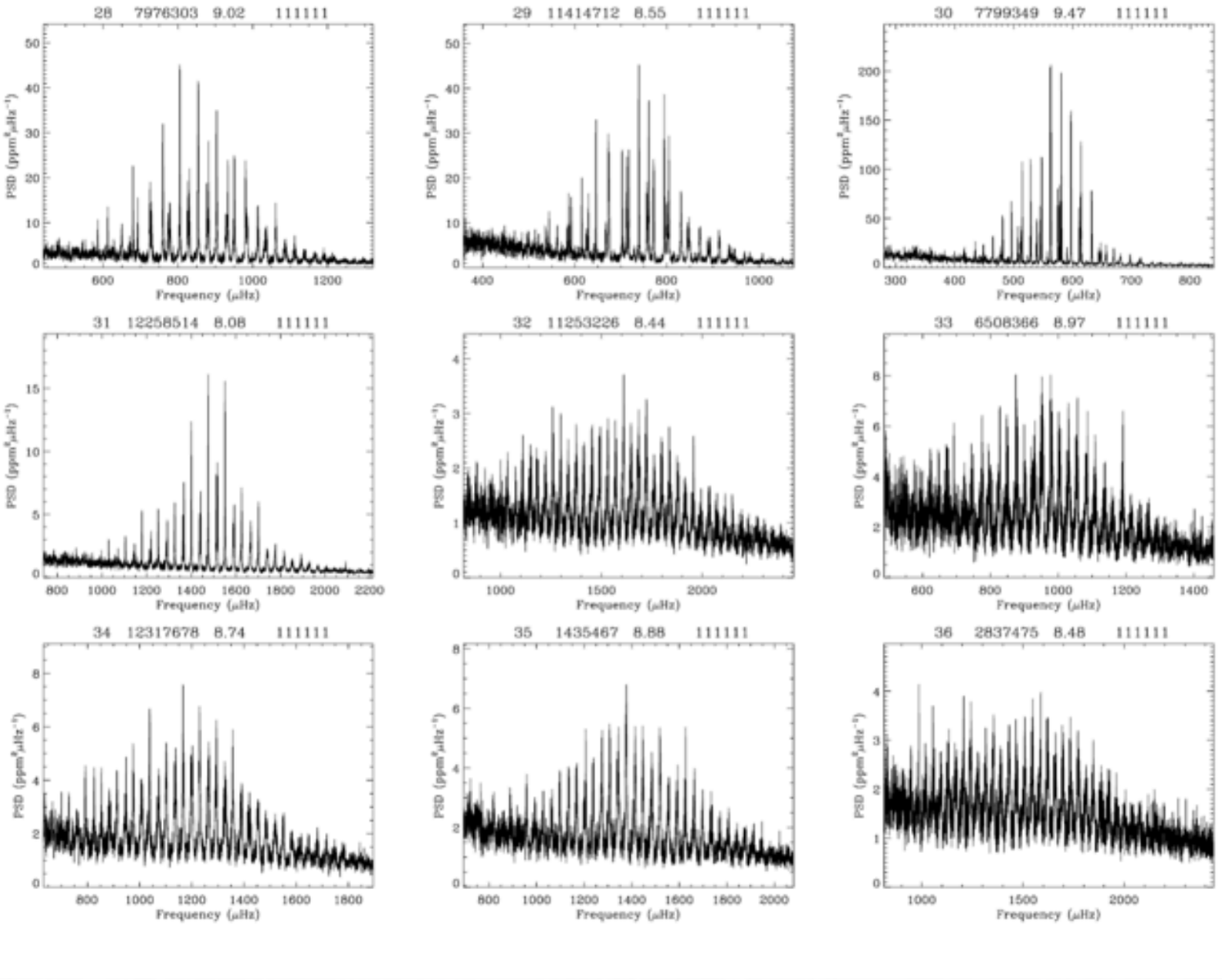
Kepler-16

(2) Kepler-10

Kepler-4

Kepler-23 (2)

Kepler-15



2)

bler-37

Kepler-8

ler-30 (3)

2)

ler-18 (3)

Kepler-16

(2) Kepler-10

Kepler-4

Kepler-23 (2)

Kepler-15

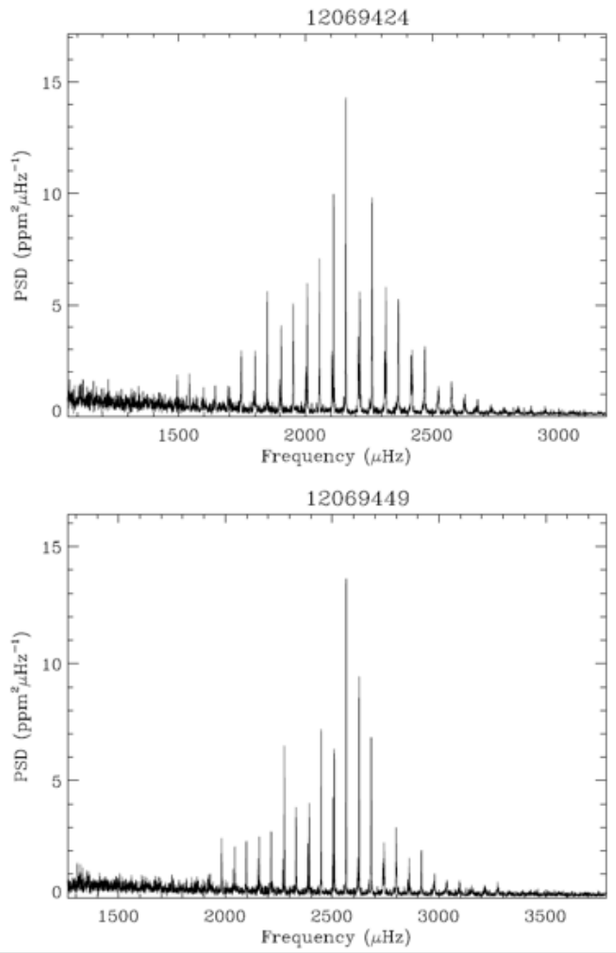
Kepler-37

Kepler-8

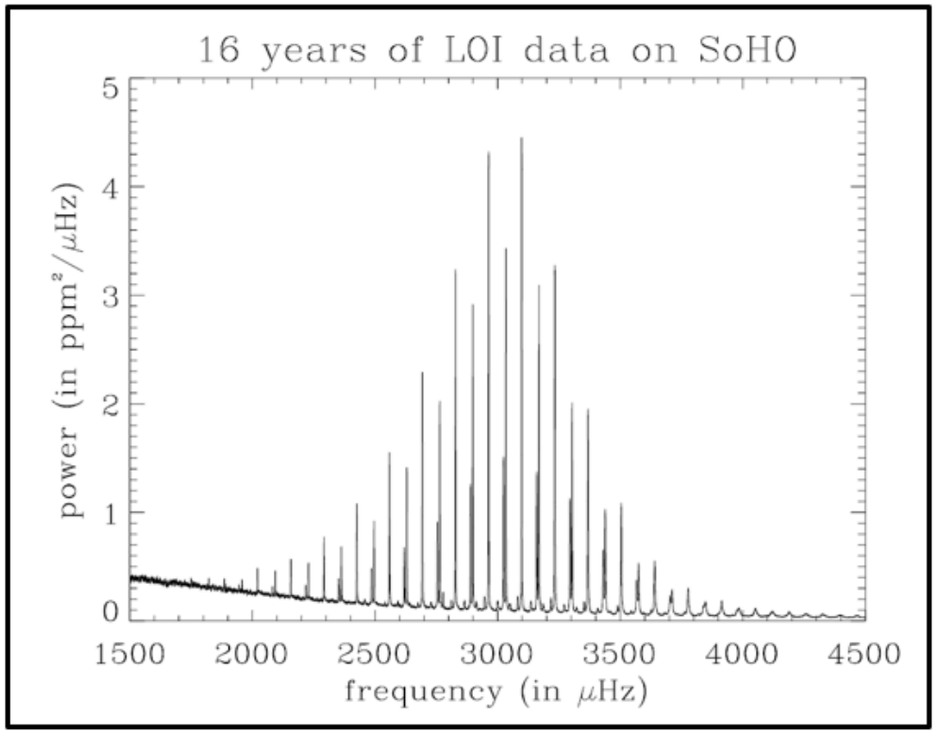
Kepler-30 (3)

Kepler-18 (3)

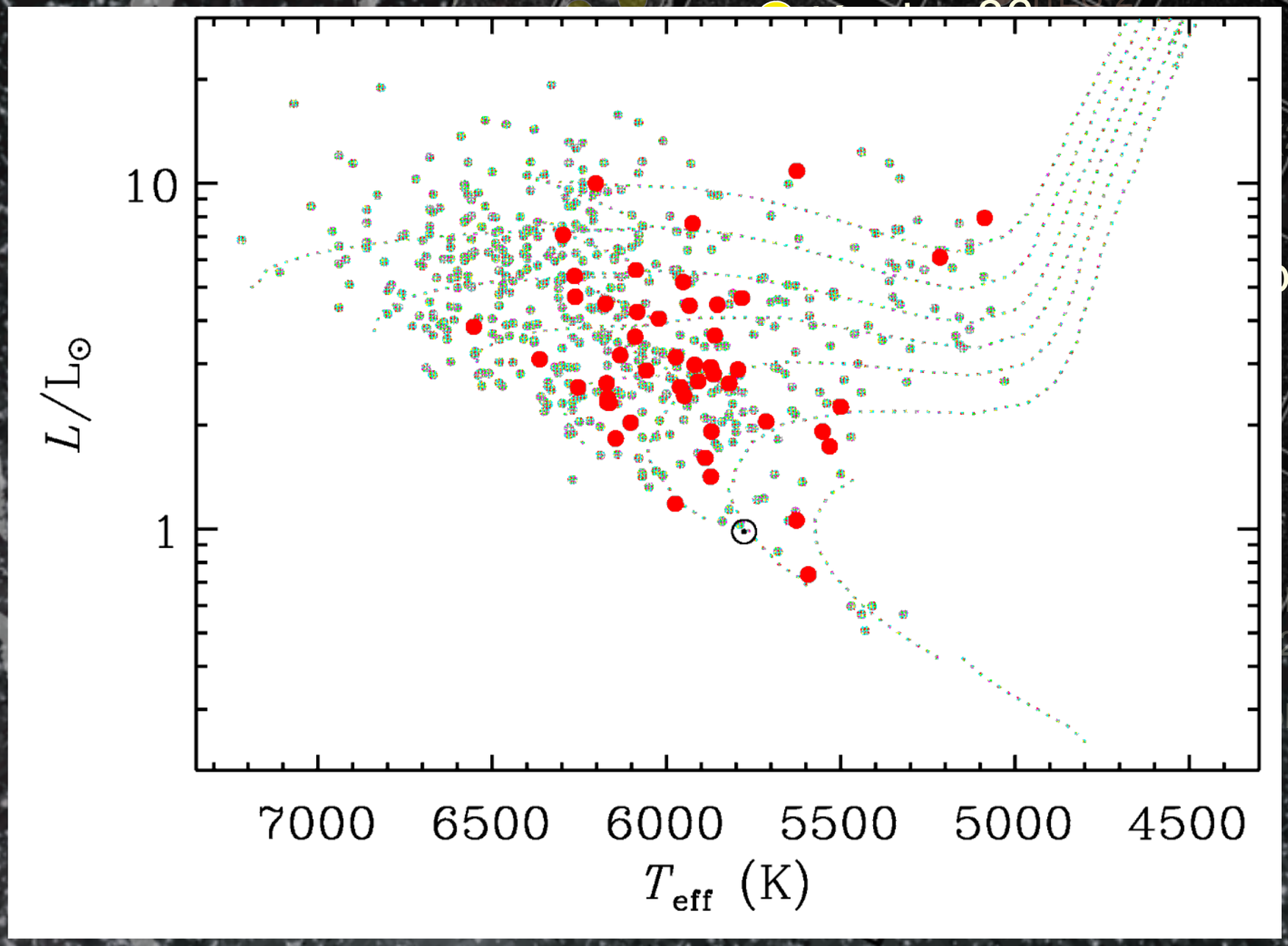
Kepler



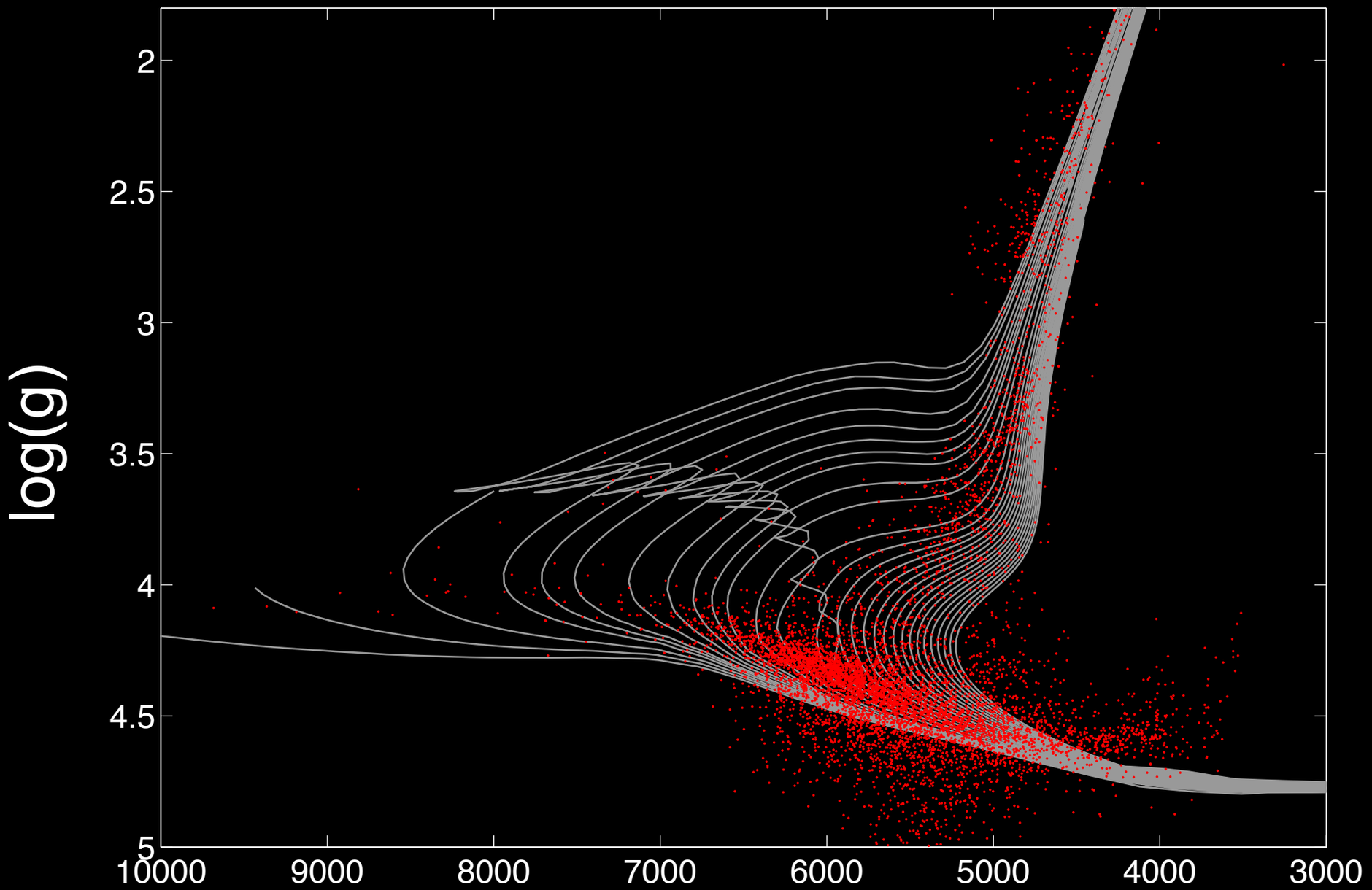
SOHO



From Thierry Appourchaux…


10
1
$L/L_\odot$
7000
6500
6000
5500
5000
4500
$T_{\rm eff}$ (K)

The Stellar Sample

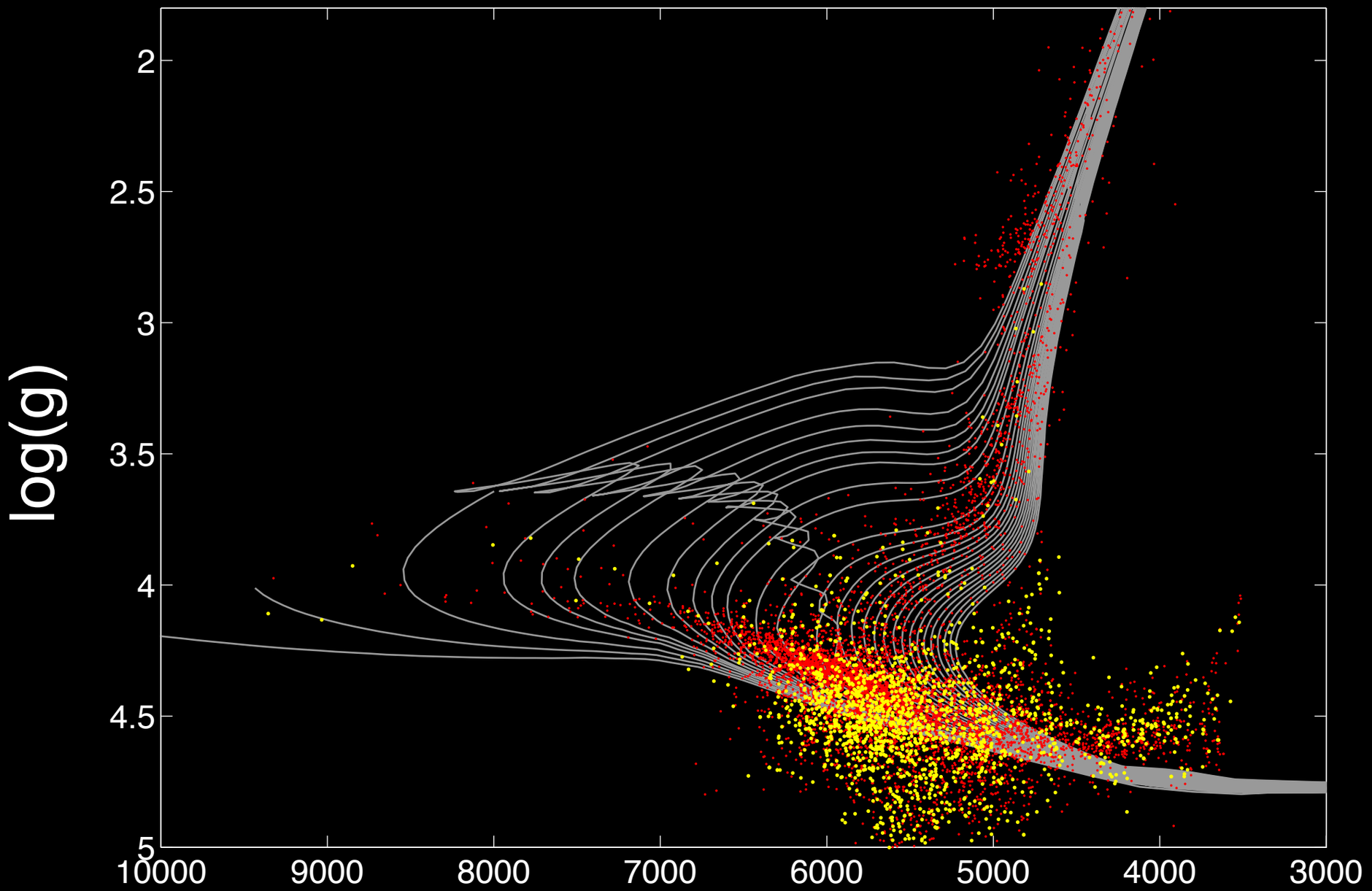


Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error

Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii

Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample



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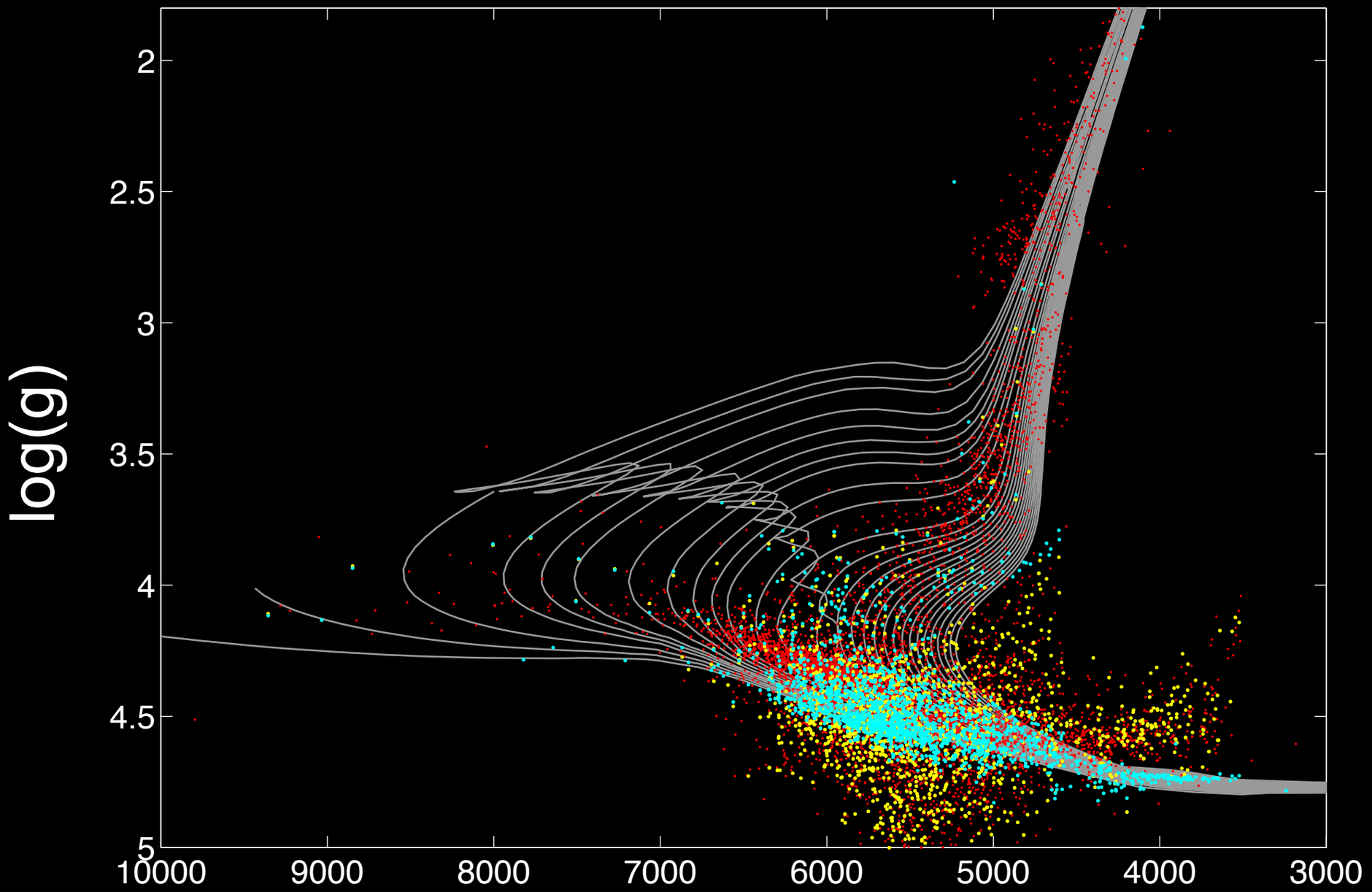
The Stellar Sample



Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error

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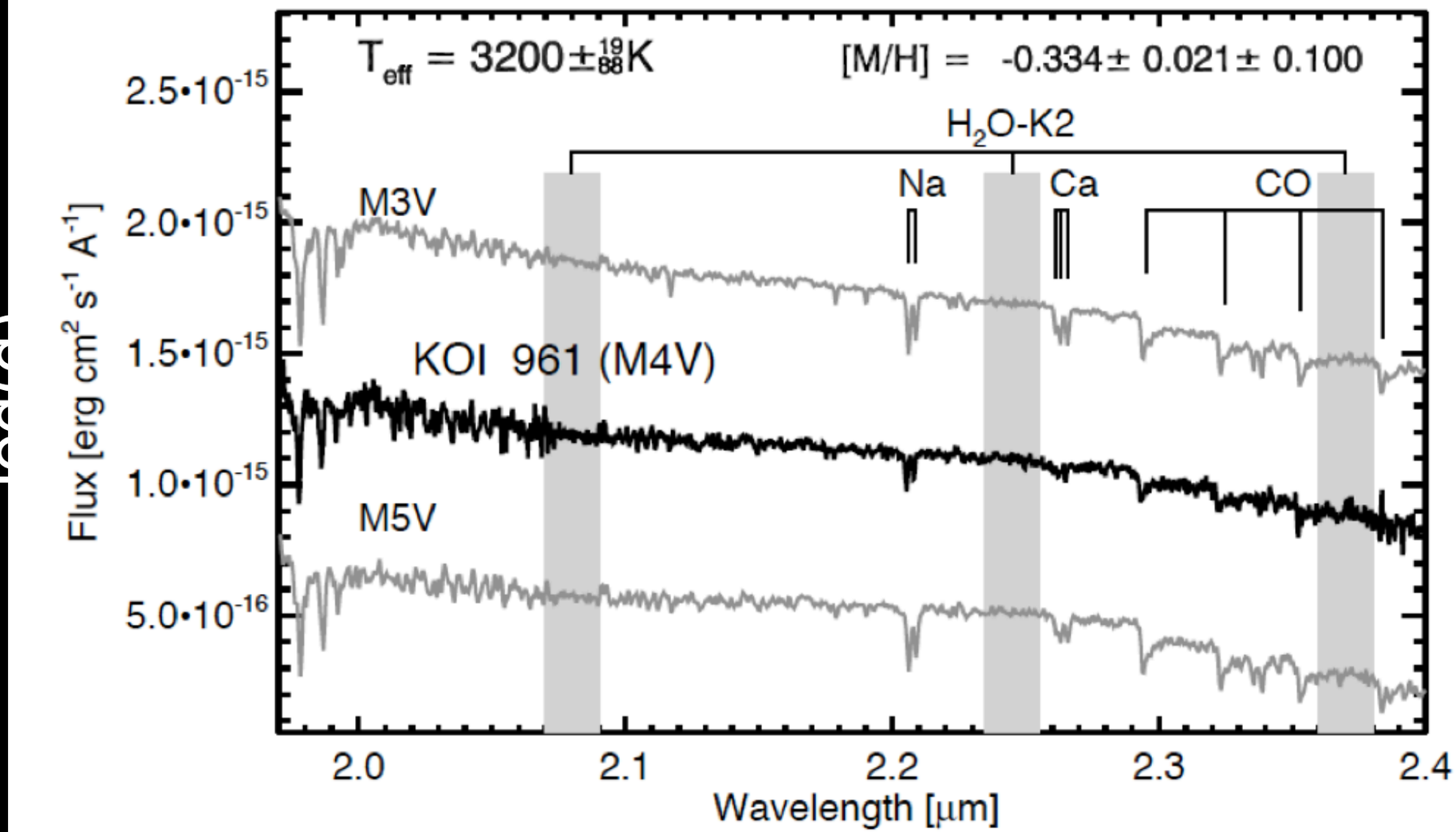
The Stellar Sample



Muirhead et al 2012, ApJ, 747, 144

Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error

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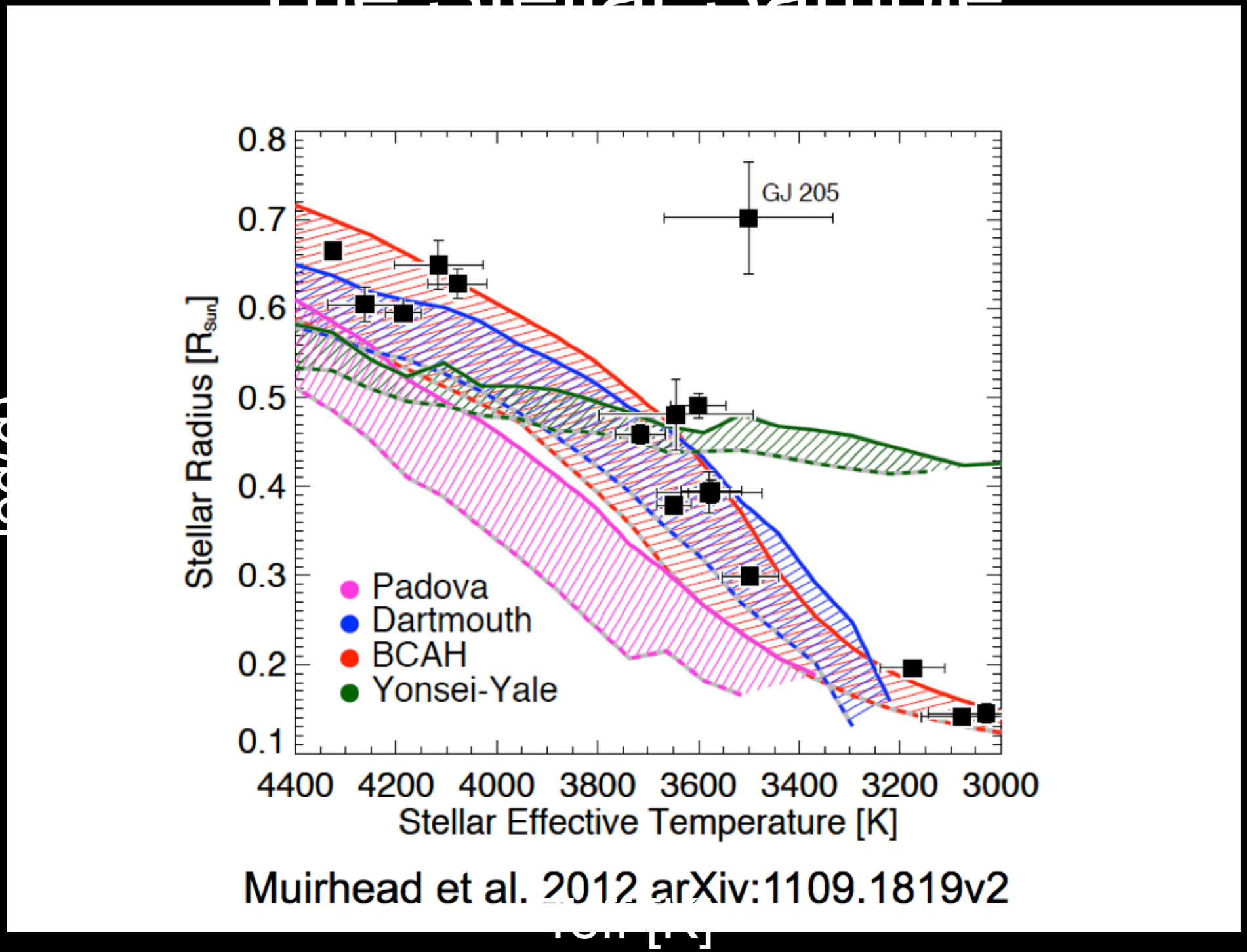
The Stellar Sample



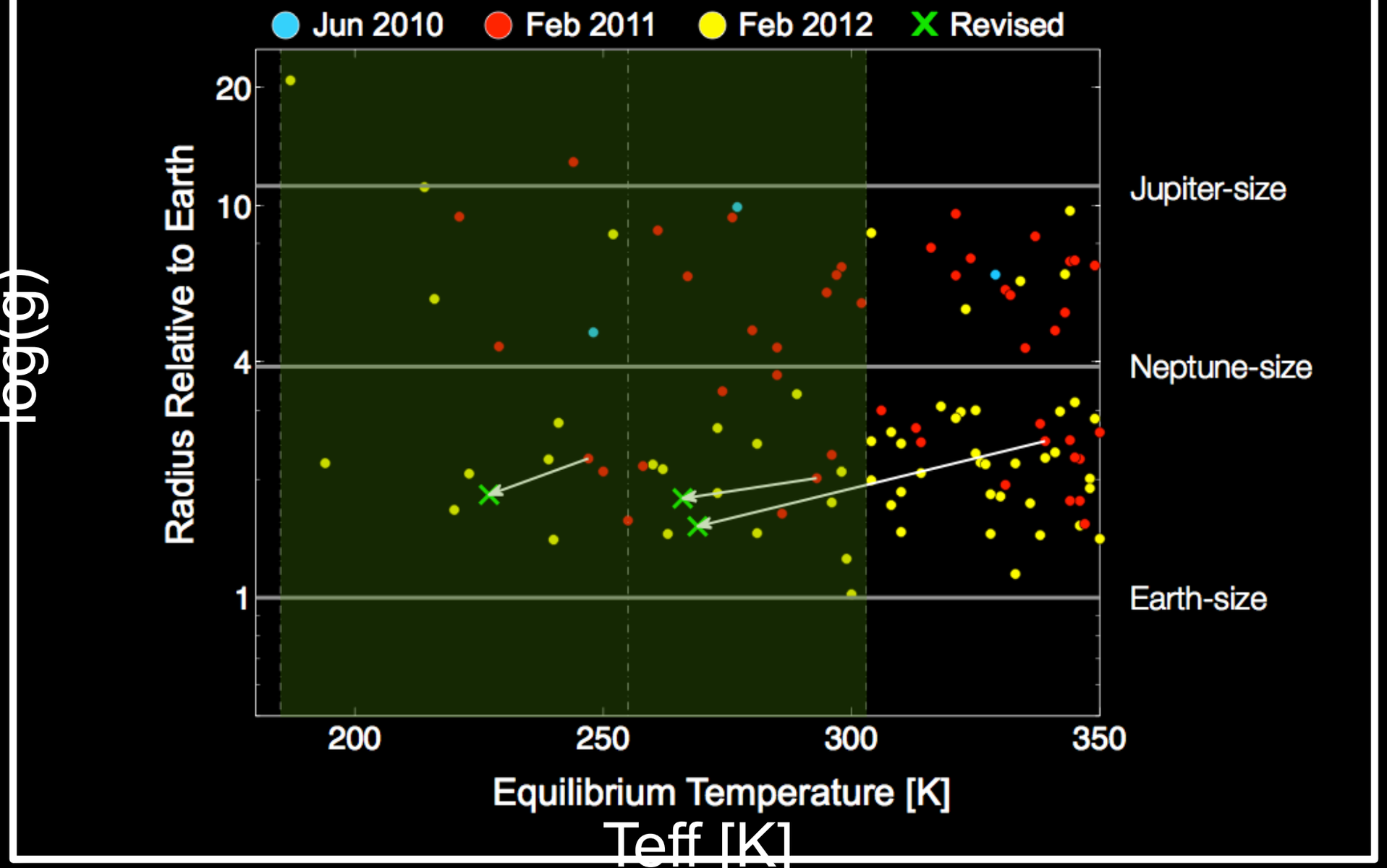
Muirhead et al. 2012 arXiv:1109.1819v2

Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error
Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii
Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

The Stellar Sample

Candidates in the Habitable Zone

Revisions from Muirhead et al. 2012, ApJ, 750, 37



log(g)

Teff [K]

Pinsonneault et al 2012: recalibration of KIC photometry; systematic Teff error

Muirhead et al 2011: IR spectra of 84 cool stars; factor of 2 smaller stellar radii

Mann et al. 2012: systematic errors in parent sample affect exoplanet statistics

Exoplanet Science in the Extended Mission

- KOI Review Team (michael.r.haas@nasa.gov)
- Stellar Characterization (your name here)
- Small Planet Completeness (jessie.l.christiansen@nasa.gov)
- Asteroseismology (gillil@stsci.edu)
- Transit Timing Variations (eford@astro.ufl.edu)
- Eclipsing Binaries (aprsa@villanova.edu)
- False Positive Tracking (Steve.Bryson@nasa.gov)
- Follow-up Observation Program (ciardi@ipac.caltech.edu)
- Other (Giant Planets, Circumbinary Planets)

Summary

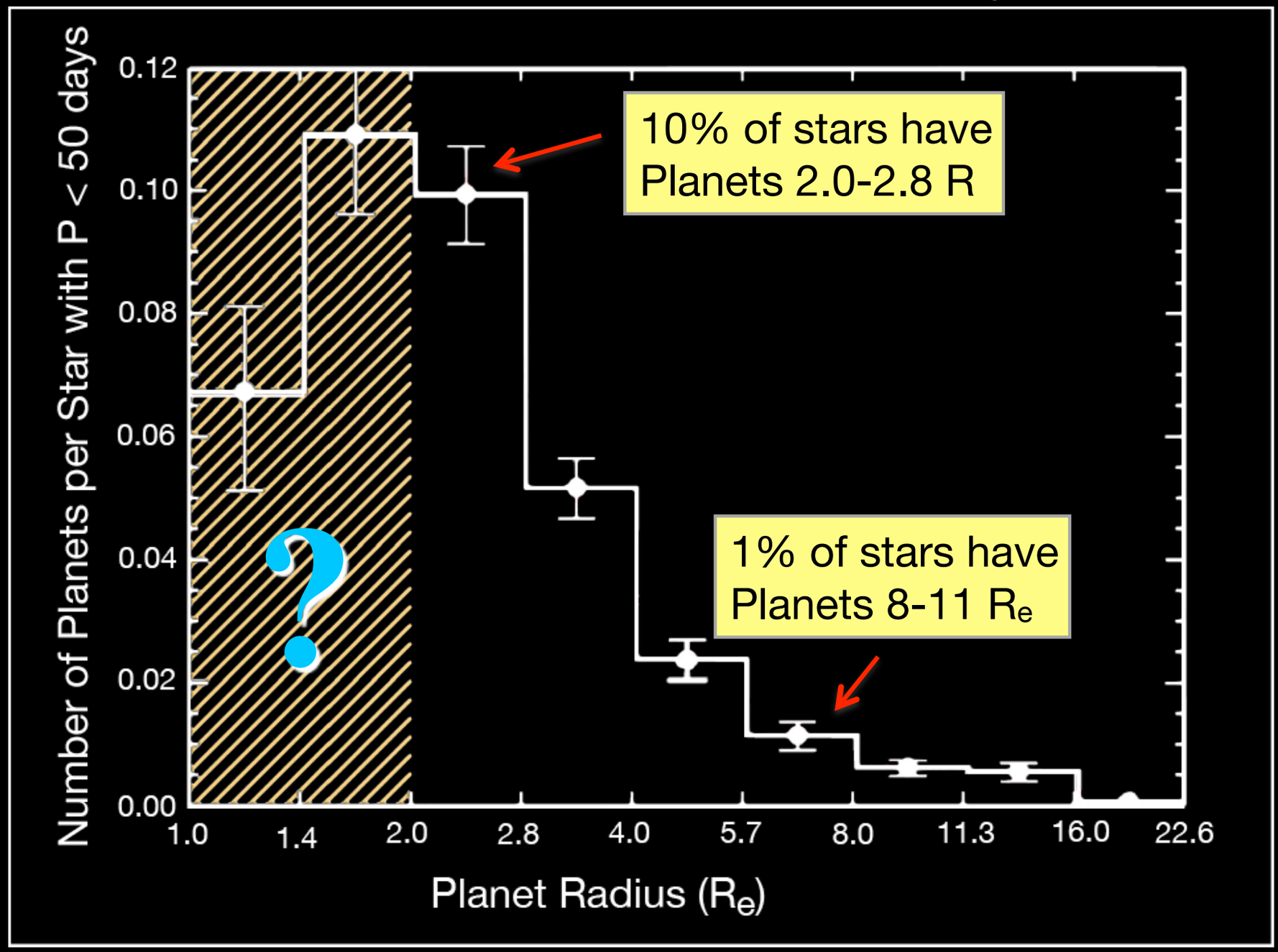
- 72 Confirmed and/or characterized planets
  - rocky, earth-size, HZ, circumbinary, multiples
- 2,321 planet candidates, 1091 of which are new this year
- 16 months of data has been search for transits
- 250 earth-size candidates, one of which (KOI-2124.01) is in/near the HZ
- Power-law increase toward small planets down to 2 R_e
- Pipeline completeness still improving
- 20% of stars observed to harbor >1 candidate
- Paucity of short-period giants in flat systems
- Small pile-up just outside of low-order resonances
- Stellar classification is high priority for reliable planet radii
- Stellar Variability (6.5-hour) is 50% higher than predicted
- Extending mission from 3.5 to 7.5 years recovers baseline performance.
- Extending mission allows for determinations of eta-Earth-size in the HZ.

Onward!
natalie.batalha@nasa.gov

Supplemental Slides

Distribution of Planet Diameters

For Orbital Periods < 50 Days



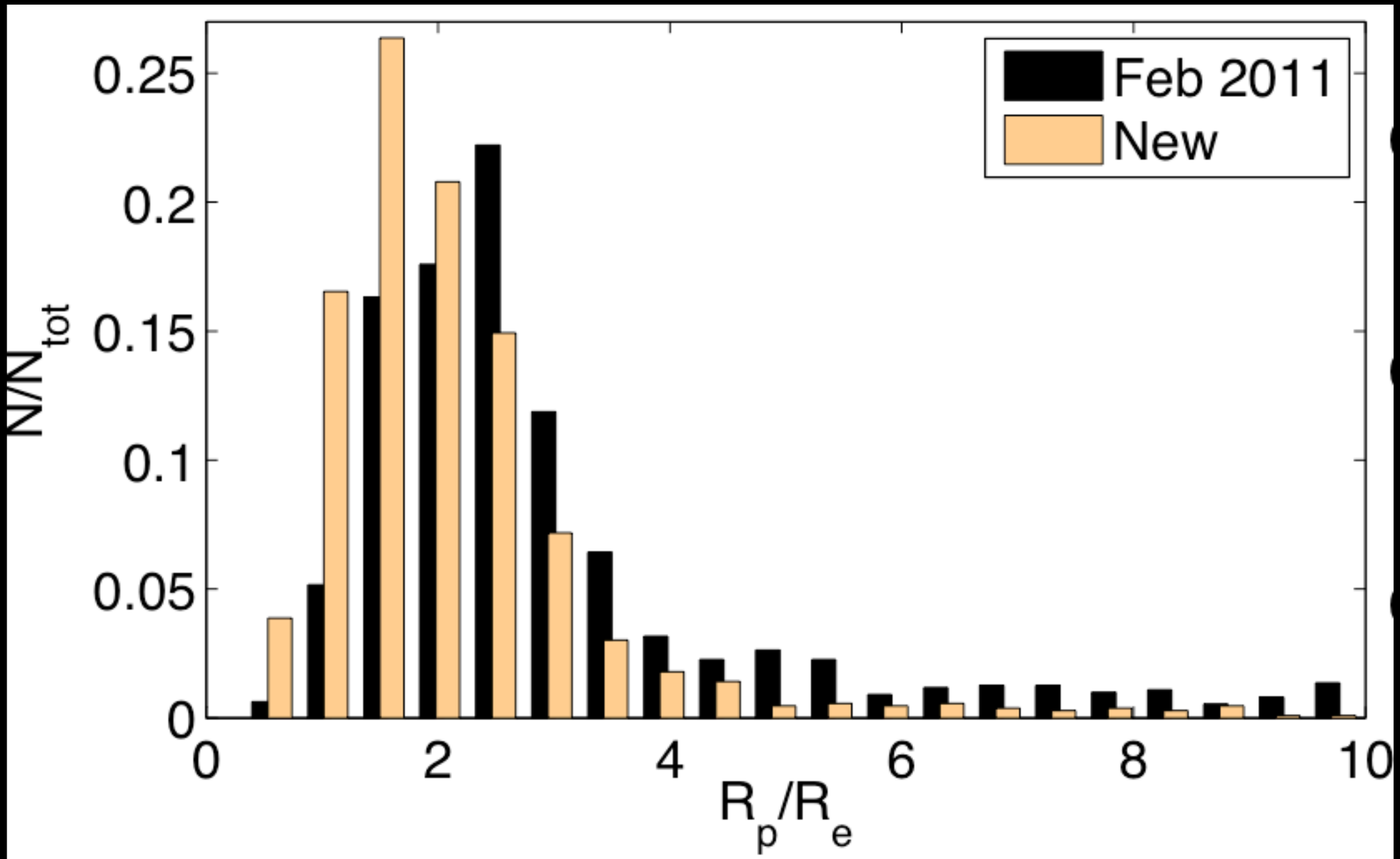
Howard et al. 2011, arXiv: 1103.2541

N(Q6)/N(Q5)

	1.25 Re < Rp < 2 Re		2.5 Re < Rp < 6 Rp
	5 < P < 50	50 < P < 150	10 < P < 125
Modeled	1.1	1.4	1.0
Observed	2.8	7.2	1.6

Gains cannot be explained solely by longer data collection.

Fractional Gains

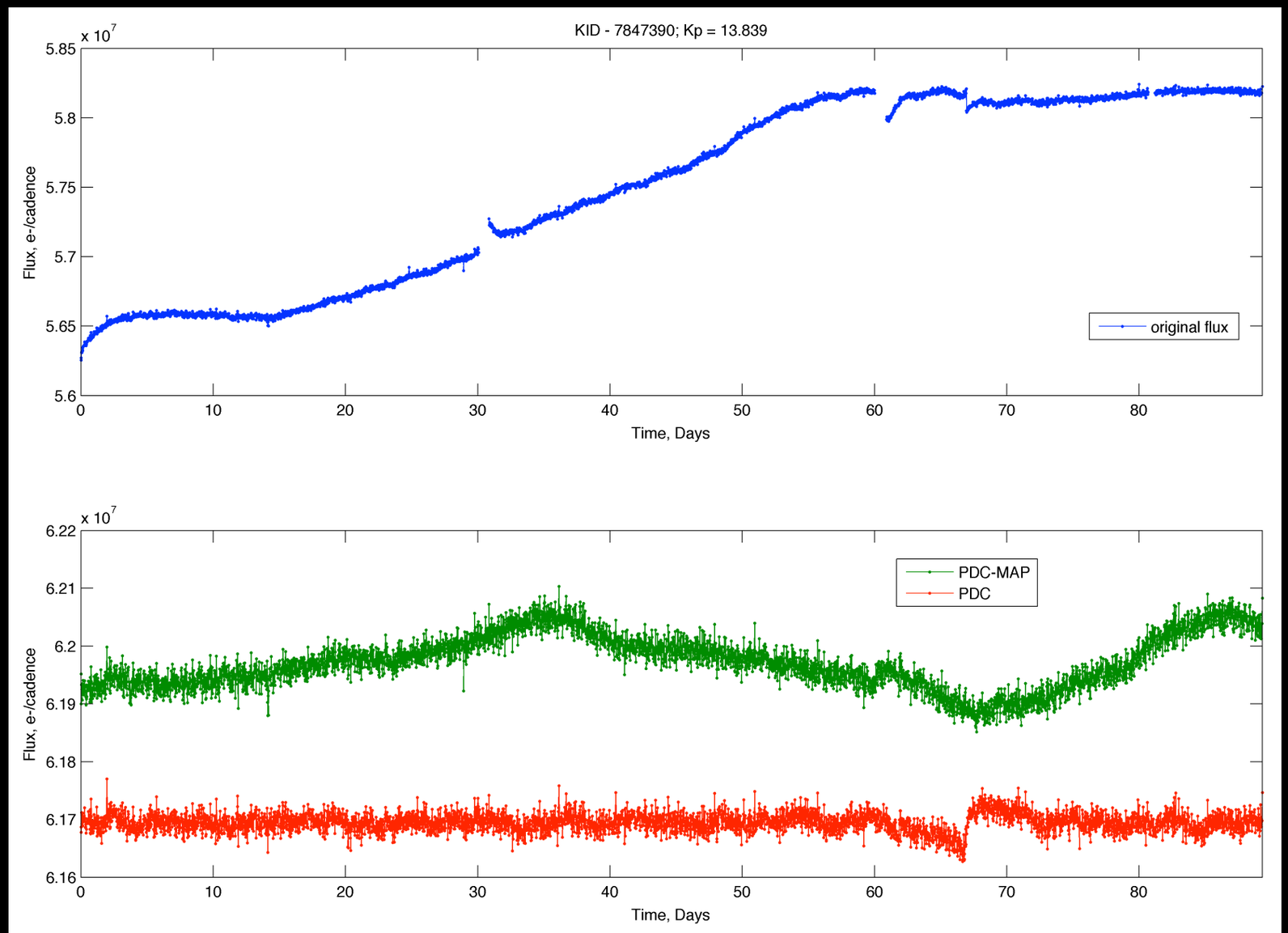


$R_p < 2\ R_e$: 197%
$R_p > 2\ R_e$: 52%

P > 50 days : 123%
P < 50 days: 85%

Factors Affecting Completeness

<u>Sudden Pixel Sensitivity Dropouts</u>:
Transit detection analysis keys off on anomalous event instead of real transits. This, also, is treated in PDC-MAP.



Original flux

PDC

PDC-MAP

arXiv:1203.1383

Impact of Measured Noise

Mission design based on a peak at 20 ppm

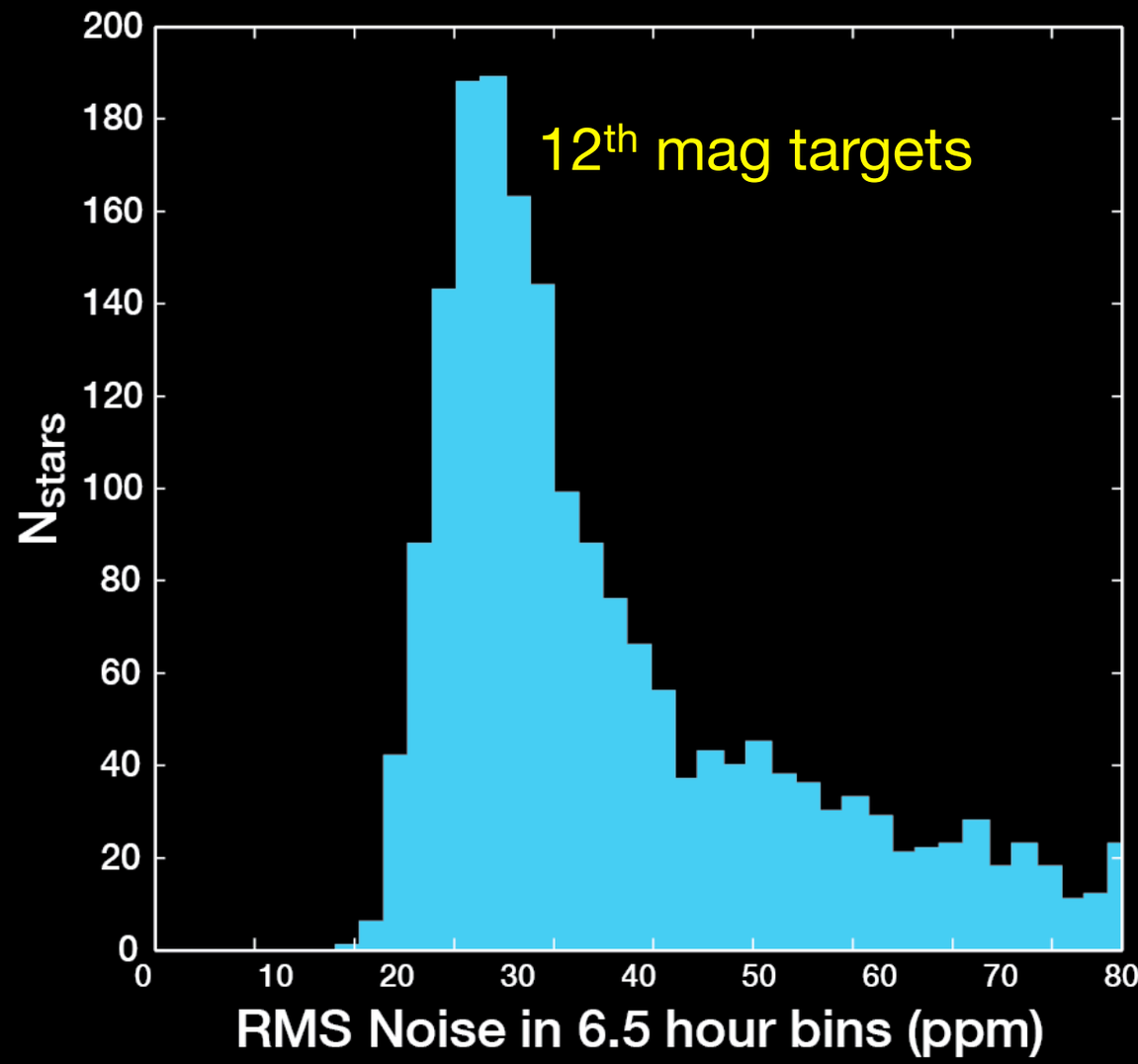
Histogram peaks at 30 ppm

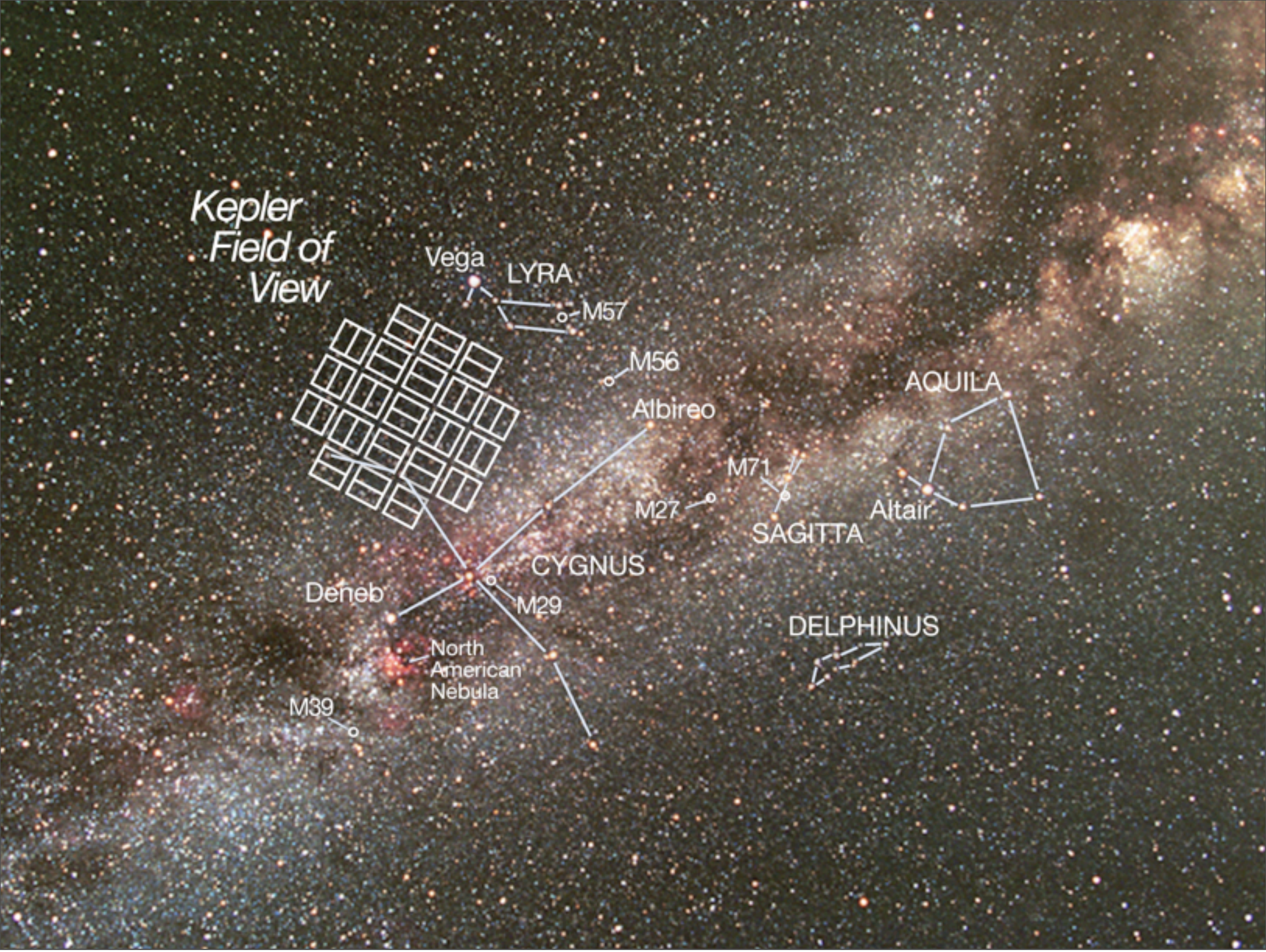
- Yields only 2% completeness for Earth analogs in baseline mission

Sensitivity improves as √t

- Noise is uncorrelated in successive transits
- Yields ~50% completeness for Earth analogs with 7.5 year mission

Noise Histogram



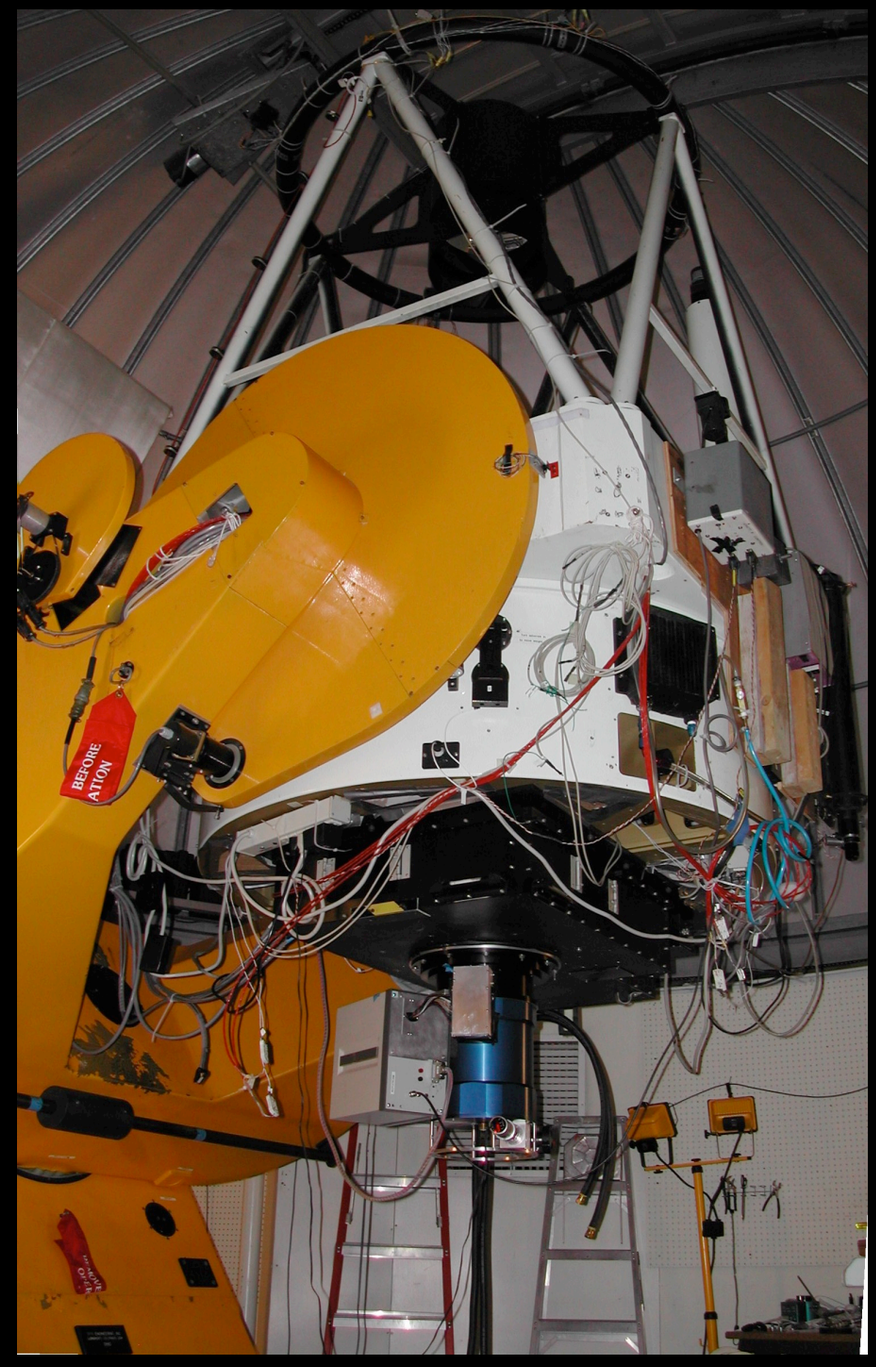

Kepler
Field of
View
Vega
LYRA
M57
M56
Albireo
AQUILA
M71
M27
SAGITTA
Altair
CYGNUS
Deneb
M29
DELPHINUS
North
American
Nebula
M39

Kepler Input Catalog

- KeplerCam, 1.2-m, Mt. Hopkins
  -SDSS g, r, i, z + D51
- Archive data
  -2MASS JHK, USNO-B
- Yields Stellar Parameters:
  -T_{eff}, log(g), log(Z), A_V, E(B-V)
  -Kp (kepler magnitude)
  -Radius

http://archive.mast.edu/kepler

Brown et al. 2012, AJ, 142, 112

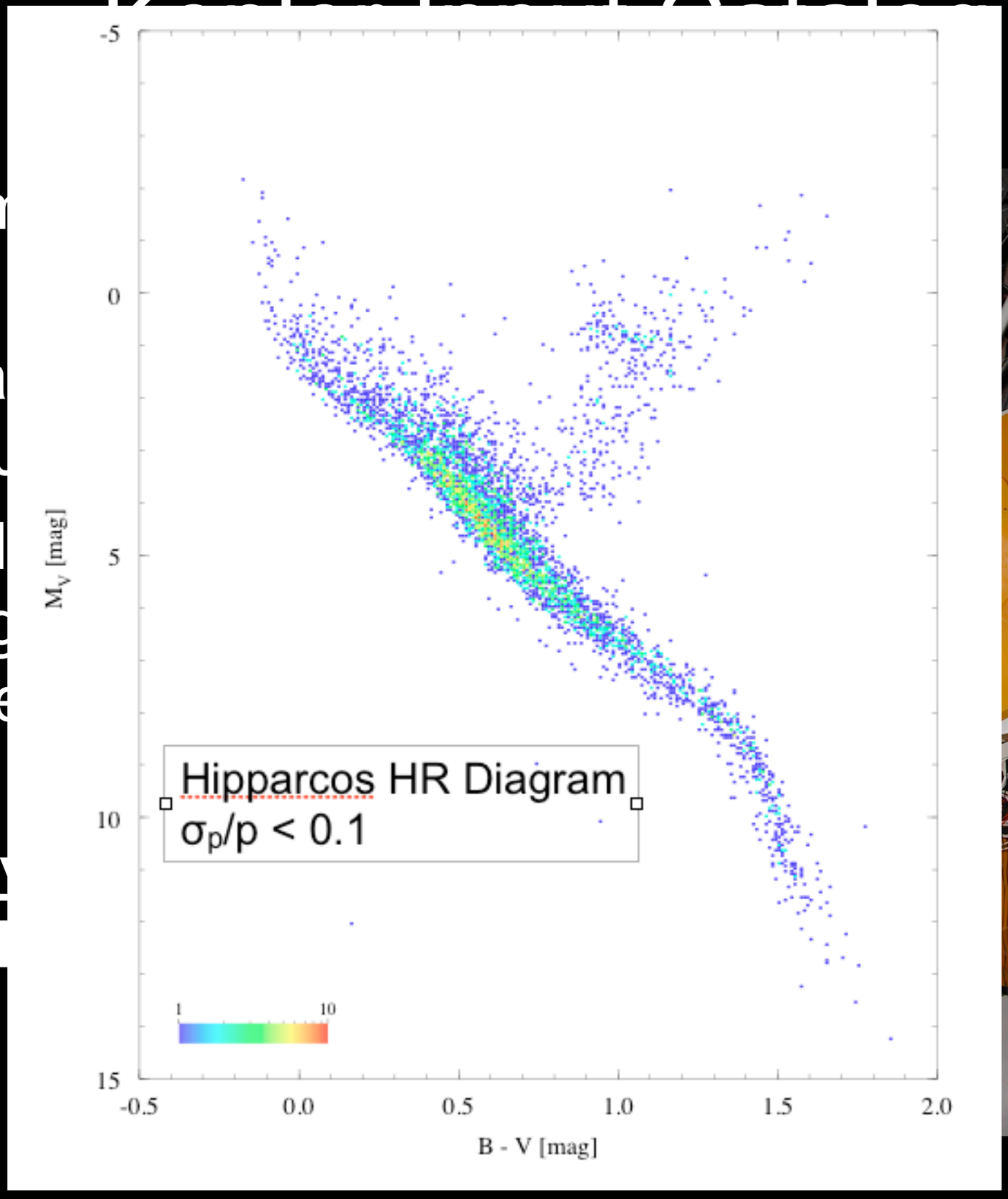


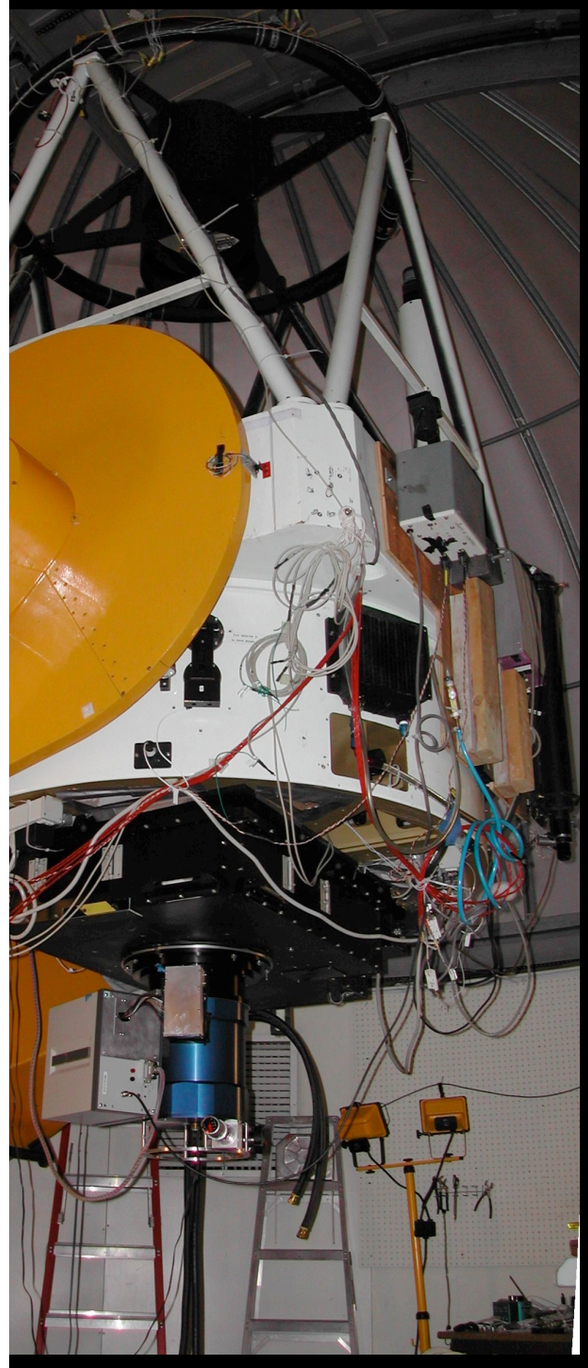
Kepler Input Catalog

- KeplerCam
  - -SDSS g,
- Archive da
  - -2MASS J
- Yields Stel
  - -T_{eff}, log(g
  - -Kp (keple
  - -Radius

http://archiv

Brown et al

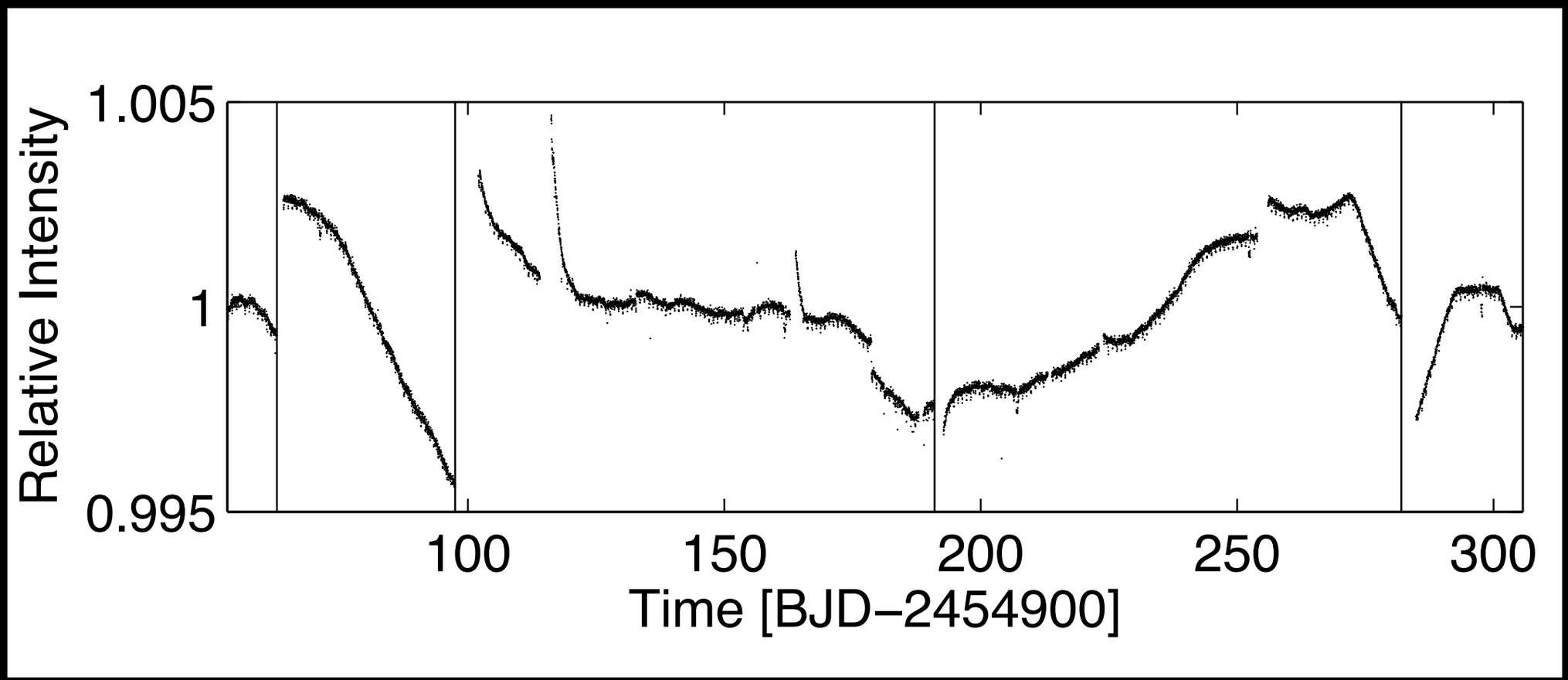




Factors Affecting Completeness

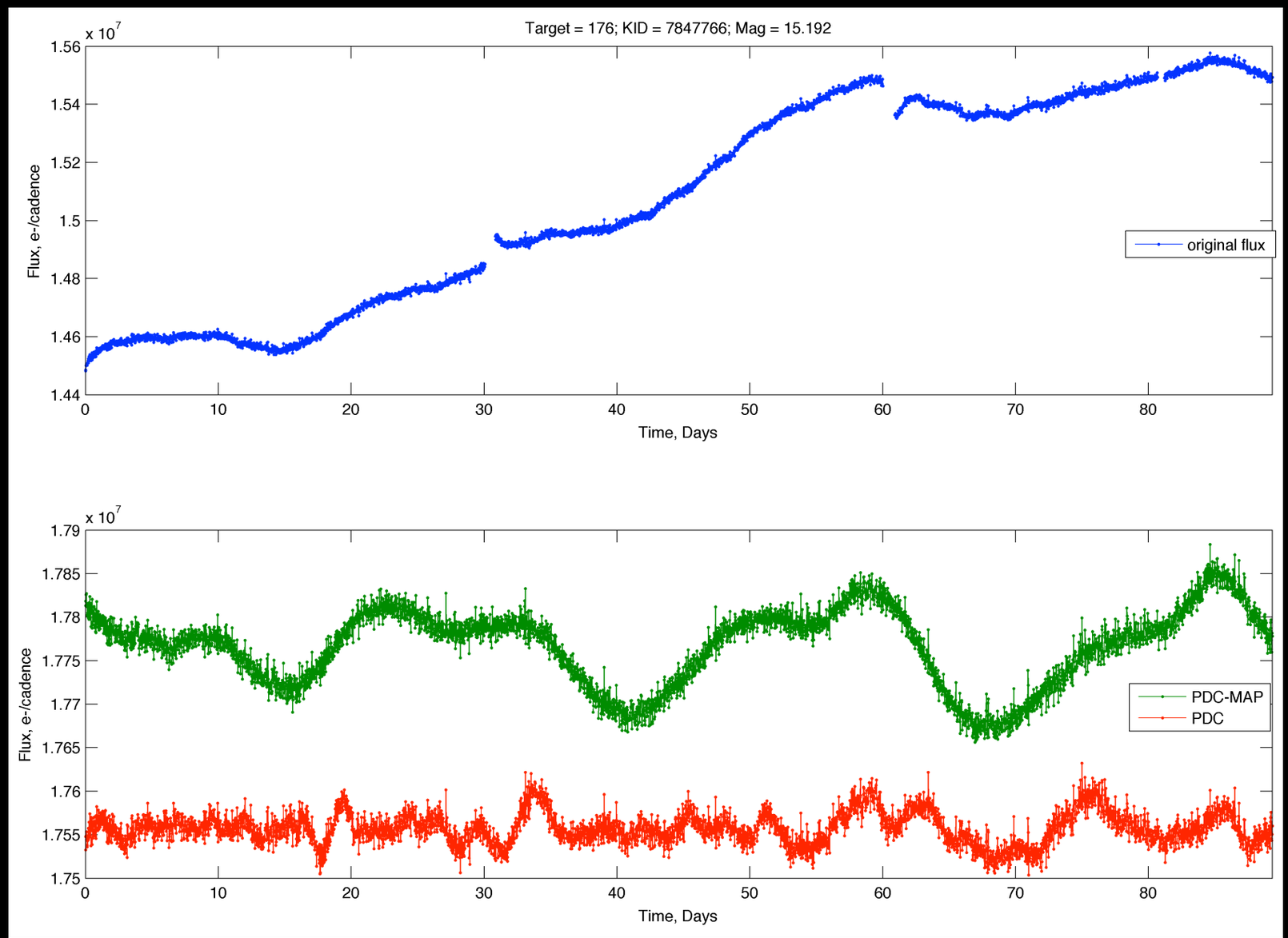
Multi-Quarter Transit Search:

- Feb 2011 catalog: analysis of Q0-Q5 data based on non- pipeline tools to detect long-period events.
- Didn't benefit from pipeline whitening filters



Factors Affecting Completeness

<u>Pre-search Data Conditioning</u>:
First generation filters occasionally introduced high frequency noise. This has been greatly improved with PDC-MAP.



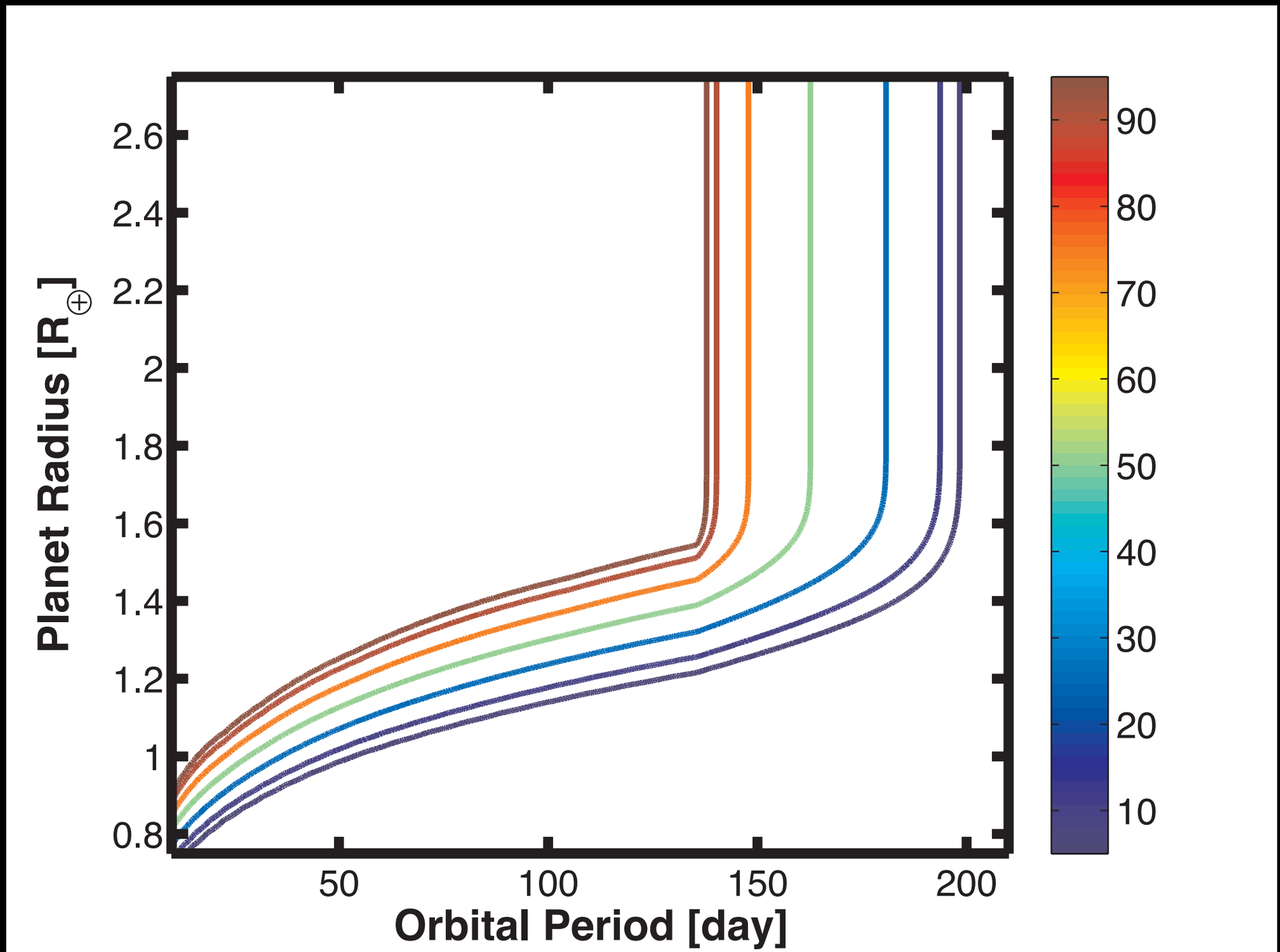
Original flux

PDC

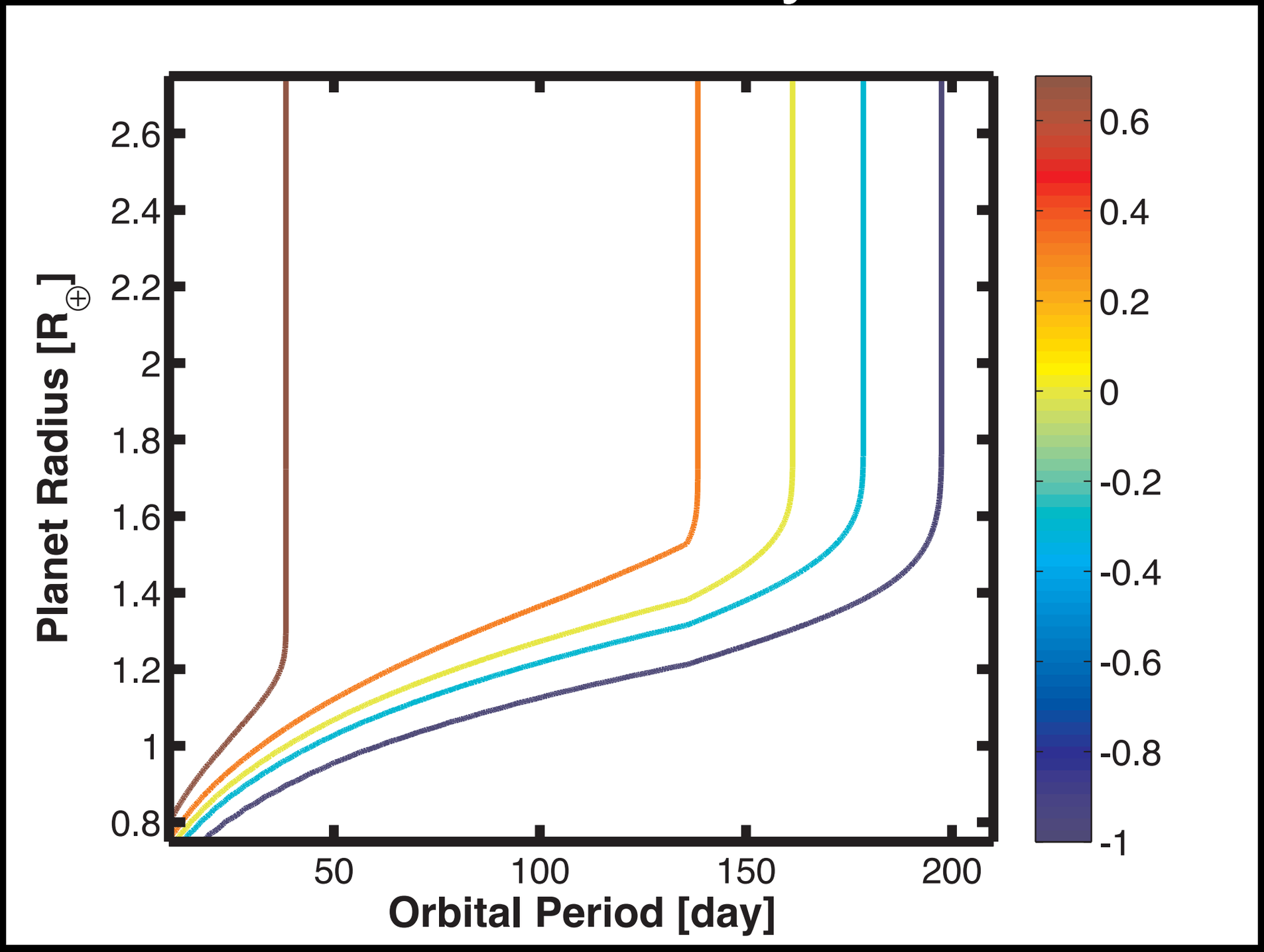
PDC-MAP

arXiv:1203.1383

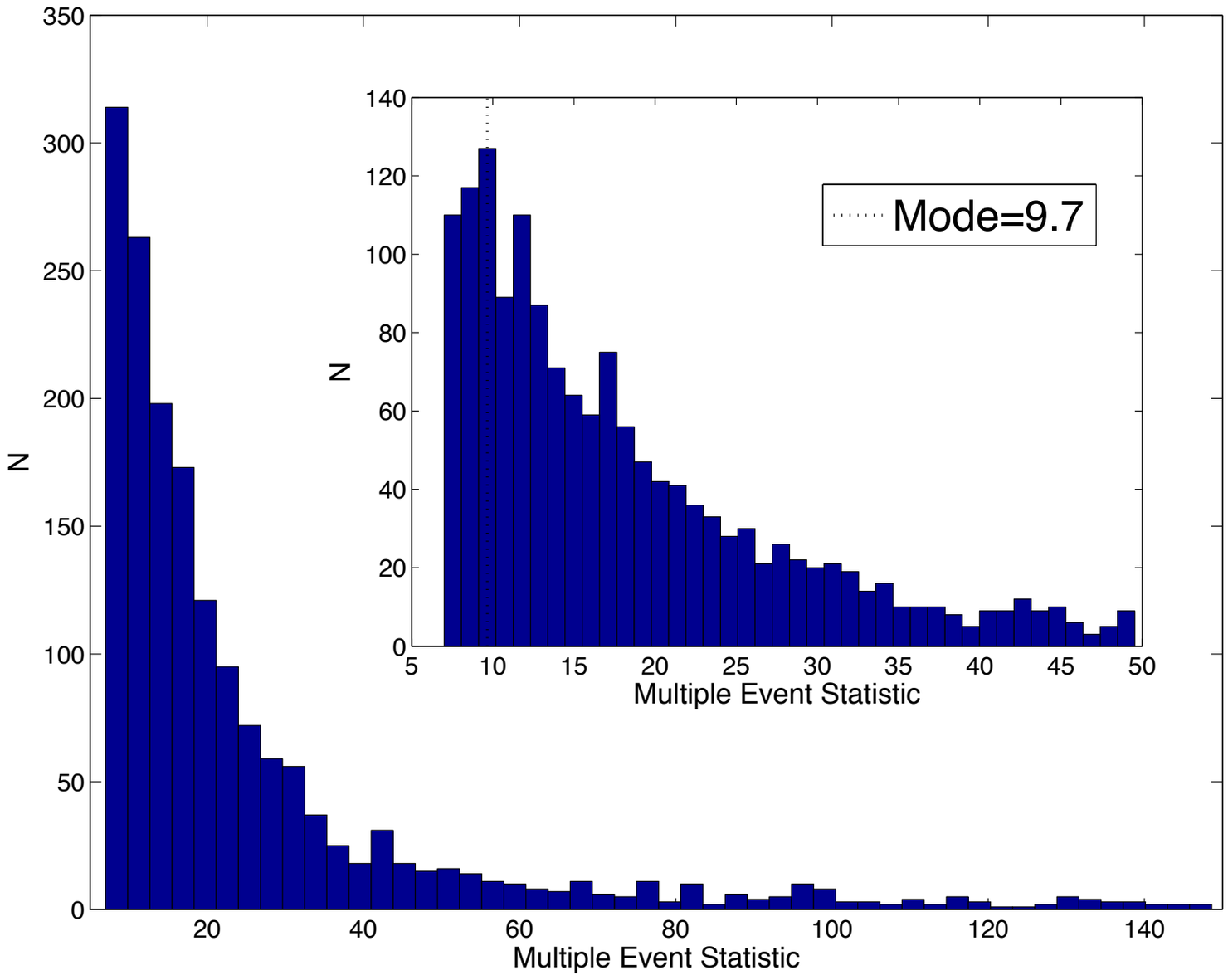
Percent Completeness



Completeness Including Transit Probability

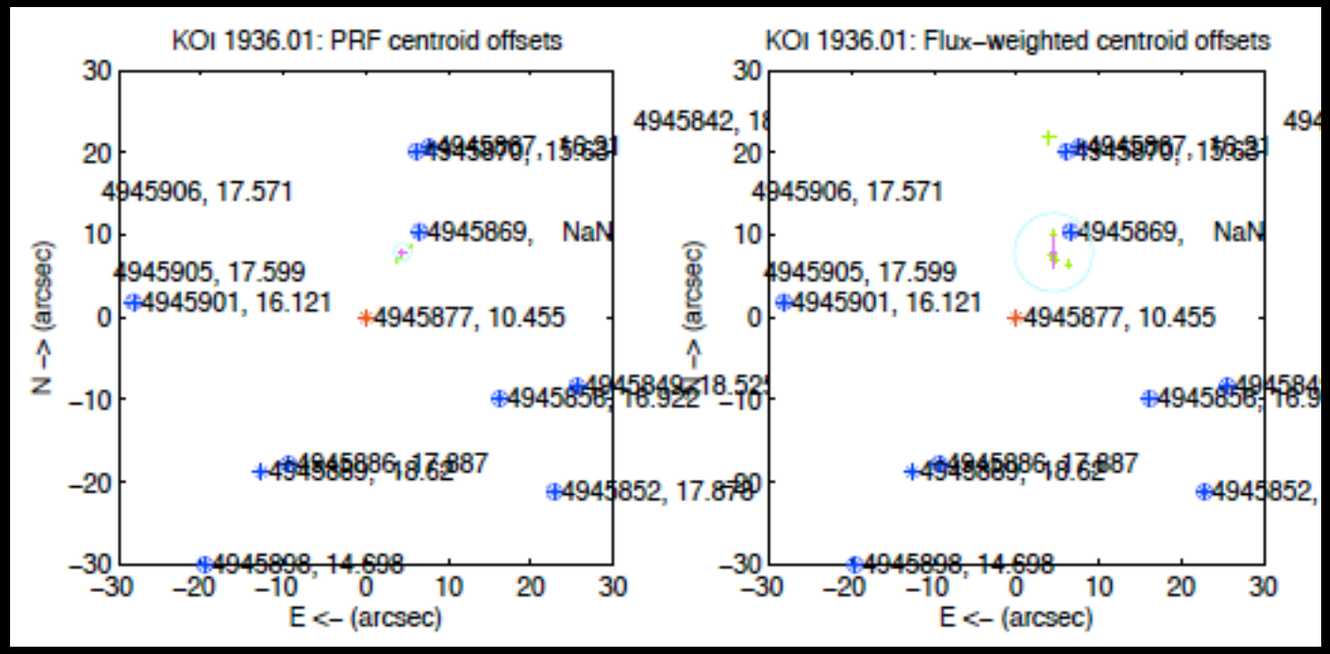


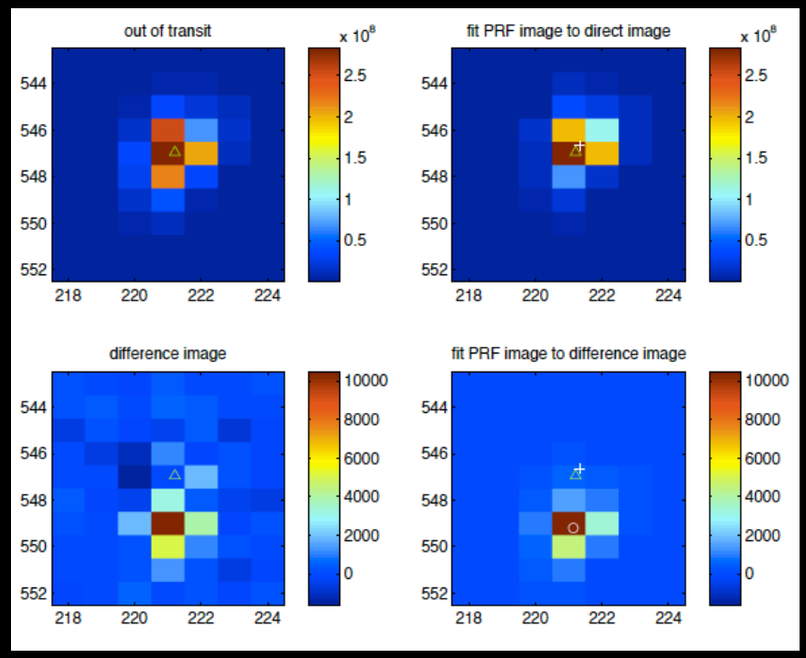
Histogram of Total SNR



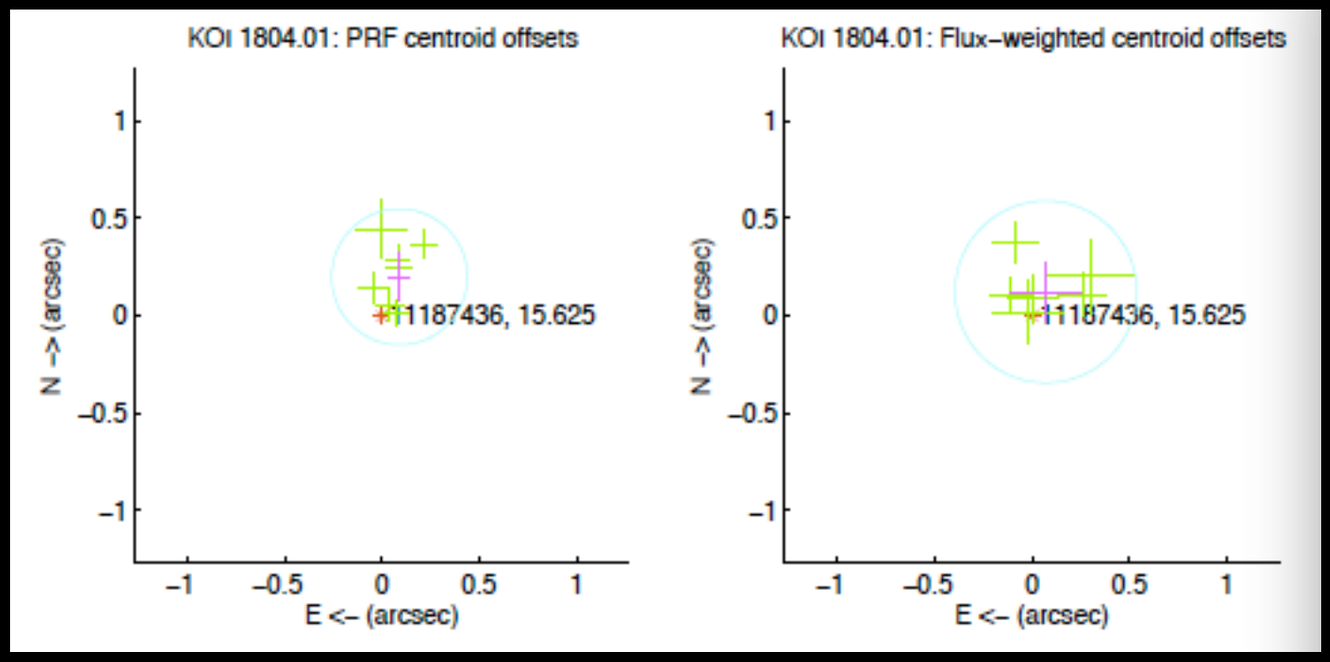
Turn-over at 9.7-sigma implies pipeline incompleteness. This should be greatly improved with PDC-MAP reprocessing.

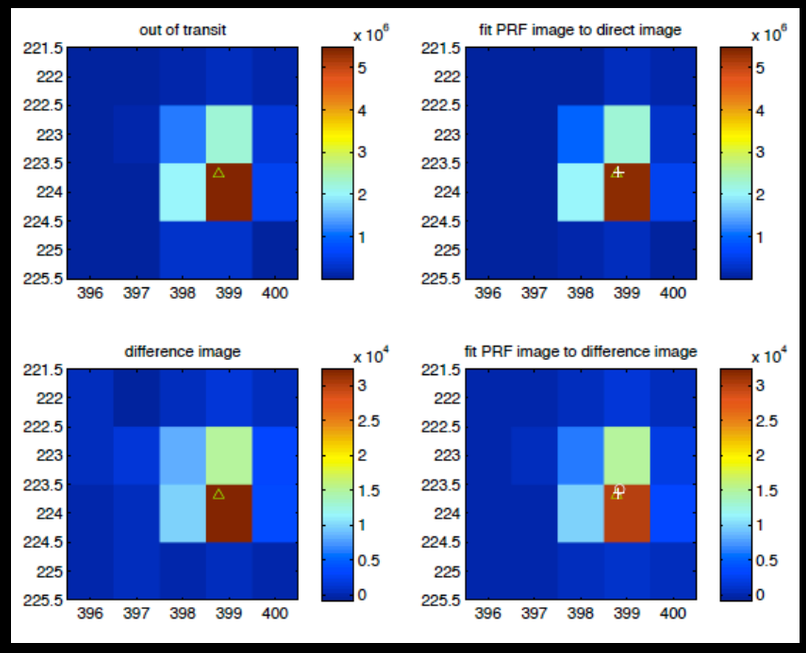
Improved Vetting Statistics





9.1 arcsec source offset





0.2 arcsec source offset

HARPS-N: 3.-6m TNG, Canary Islands; commissioned in the spring